Electrical Engineering

August
1938

Published Monthly by the
American Institute of Electrical Engineers

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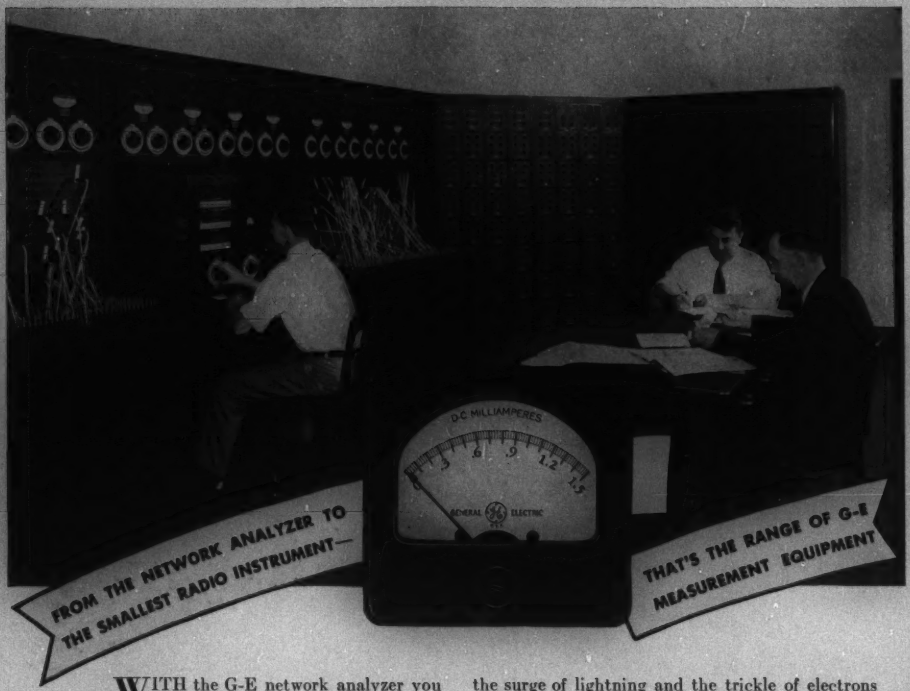

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Electrical Engineering

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The Cover

A telegraph relay for high-speed submarine cables, enlarged to approximately double diameter

Bell Tel. Labs. photo

High Lights

Subharmonic Currents. Circuits containing iron-cored inductors, which become saturated so that their reactances do not remain constant, may carry current having a frequency different from that of the applied voltage—in other words, a "subharmonic" current. Recent use of series capacitors to offset inductive voltage-drop in power-transmission systems has increased the importance of subharmonic oscillations in engineering practice. A simplified mathematical analysis reveals something of the nature and occurrence of such oscillations (*Transactions pages 423–31*).

Ferroresonant Circuits. The "ferroresonant" type of nonlinear circuit containing a resistor, a capacitor, and a saturable-core reactor has been applied to several engineering problems in control. Two papers in this issue describe the characteristics and applications of circuits of this type: One (*Transactions pages 469–76*) describes a sensitive and stable power-controlling device; the other defines some of the critical factors affecting stability in such nonlinear circuits (*Transactions pages 444–52*).

System Recovery Voltage. If an arc-interrupting device is to operate successfully, the insulation recovery-voltage characteristic of the device should be higher than that of the system. Consequently, a sound application of protector tubes requires a broad knowledge of the characteristics of power transmission systems. A survey of the recovery-voltage characteristics of typical systems has been conducted, and the results are presented in this issue (*Transactions pages 432–43*).

Overvoltages Caused by Short Circuits. During an unbalanced fault on a power system a high voltage may develop across the unfaulted phase or phases. Overvoltage may be caused by the short circuit itself, and a further overvoltage by the clearing of the fault. Some such excessive voltages may be reduced or suppressed completely by the use of amortisseur windings on the synchronous machines supplying the fault current (*Transactions pages 453–68*).

Electrical Precipitation, as a means of removing dust particles from air, is a familiar process. Less well known are the equally spectacular applications of the method in industry, such as the reclamation of valuable materials from waste gases or the purification of gases for subsequent use. The evolution and application of electrical precipitation are reviewed in this issue (*pages 332–8*).

Pamphlet Papers Available. Response to the offer and order form published in the July issue was heavy, and some additional papers now are out of stock. However, a limited stock of some 70-odd papers prepared in pamphlet form for use at the winter convention, the North Eastern District meeting, and the summer convention still is available (*page 366*).

Engineers and Economics. The engineer in his relation to current economic trends provides a fertile field of political and sociological speculation. An eminent leader in research and past president of the Institute has analyzed some of these trends in economic philosophy, and has attempted to clarify the position of the engineer (*pages 339–44*).

Rural Electrification. In England some of the problems differ from those prevailing in the United States. Such differences are pointed out, and a typical British rural electric system is described (*pages 345–8*).

Summer Convention. Supplementing the initial reports published in the July issue, a full report covering the activities of the recent summer convention in Washington, D.C. may be found in this issue (*pages 349–51*).

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Coming Soon. Among special articles and technical papers now undergoing preparation for early publication in ELECTRICAL ENGINEERING are: an article describing the electrification of the San Francisco Bay Bridge for railway operation, by Paul Lebenbaum (M'13); a summer convention address "Progress in Weather Forecasting," by W. R. Gregg, chief of the Weather Bureau; a description of the new transcontinental telephone lines by J. J. Pilliod (F'34); four technical papers concerning distribution system voltage regulation—one on planning and operation by T. J. Brosnan (M'34), one on the characteristics of regulating equipment by P. E. Benner (A'28) and G. S. Lunge (A'23), one discussing the problems of a rural distribution system by G. H. Landis (M'33), and one pertaining to periodic voltage surveys by R. W. Burrell (A'35) and W. E. Appleton (A'35); four papers descriptive of industrial applications of new electrical equipment—a description of regenerative tension control for winders in paper mills by H. W. Rogers (A'12), a comparison of methods of stopping squirrel-cage induction motors by W. I. Bendz, suggestions for the use of capacitors for power-factor correction in industrial plants by C. E. H. von Sothen, and a description of a photoelectric weft-straightener control for textile mills by C. W. LaPierre (A'28) and A. P. Mansfield; two papers pertaining to power transformers—data on corona voltages of typical insulating materials under oil by F. J. Vogel (A'21), and a paper describing d-c transformers by T. C. Lennox (A'23) and E. V. De Blieux (A'34); a paper giving further data concerning multiple lightning strokes, by K. B. McEachron (F'37); and a paper reporting further experience data concerning protector-tube application and performance on 132-kv transmission lines, by Philip Sporn (F'30) and I. W. Gross (A'12).

DISCUSSIONS

Appearing in this issue are discussions of the following previously published papers:

Basic Sciences

Matrices in Engineering—Pipes 477
The Properties of Three-Phase Systems Deduced With the Aid of Matrices—Reed 477

Cables

Oil Oxidation in Impregnated Paper—Whitehead and Jones 482
The Current-Carrying Capacity of Rubber-Insulated Conductors—Rosch 484
Mechanical Uniformity of Paper-Insulated Cables—Wyatt, Smart, and Reynar 486

Electrical Machinery

Corona Voltages of Typical Transformer Insulations Under Oil—Vogel 478
A Formula for the Reactance of the Interleaved Component of Transformers—Dwight and Dzung 480

Statements and opinions given in articles and papers appearing in ELECTRICAL ENGINEERING are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ ELECTRICAL ENGINEERING is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). ¶ Copyright 1938 by the American Institute of Electrical Engineers. Number of copies this issue—20,700.

A Message From the President

IN THIS, my first official expression to the membership of the Institute as a whole, I think I cannot do better than to say again what I said at the annual meeting in Washington when Doctor Harrison formally announced the election of his successor.

To acknowledge the receipt from our distinguished Institute of a great honor would, in the present instance, be impossible since such acknowledgment would presuppose some measure of desert.

One would have to be a very great engineer, indeed, worthily to stand in the place of those heroic figures who have made our branch of the profession what it is. If we keep alive and undimmed the light which they have kindled, we shall do well indeed. Yet, in a sense, we may, in all humility, find membership in the Institute in any of its grades, service in any of its offices, or a place on any of its committees a high measure of distinction in that we have received recognition of our spiritual kinship with and devotion to those who have made the Institute and the profession something infinitely finer and greater than any one of us alone can be.

Here, because of the quality that was in the founders, and perhaps, too, because of those things in electrical engineering which attracted them to it when it was only a vision and a promise, we find a field in which we exercise the utmost that is in us, whether of intellectual power or of those finer qualities of the spirit which are the source of a genuine professional attitude.

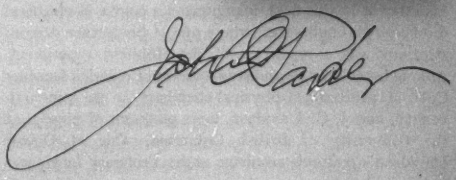
It is no accident but rather the very essence of our calling that in the Institute fact transcends mere opinion; that where the limitations of precise knowledge require the exercise of judgment opinions can be vigorously advanced without rancor; that the history of the Institute is remarkably free from politics and strife on the one hand and from suppression or coercion of expression on the other. This heritage is handed on to us as a vital thing. We will pay devotion to the founders and honor ourselves in keeping it alive, adapting our specific processes to the changing requirements of each new day while holding fast to that fundamental zeal for truth and for selfless devotion to making truth serve the needs of mankind which characterized our predecessors.

No one could have attended the Washington convention or have heard the reports of Section activities there presented without being impressed by the fact that the fine fraternity of aspiration and idealism which is in the membership assures for our calling, as represented in the Institute, a future worthy of its past.

Engineers are idealists, in all that the word implies of vision and faith and courage, but the idealism of the engineer is not a nebulous thing, remote from reality. So it comes about that the Institute finds most realistic expression for its finest aspirations in the day-by-day conduct of its affairs. The Sections are strong and stand on their own feet. The excellent staff at headquarters, the board and the officers of the Institute belong to the membership and serve the Institute as the members direct. This is no organization built from a center out. On the contrary your officers can give the highest expression to the purposes of the Institute only as the members either personally or through their Section representatives guide and advise, and above all else as each member actively participates in the conduct of his Section meetings.

Our best expression of our professional attitude would be feeble if it did not reflect itself in so humdrum a thing as a growing membership and a strong financial status. Thanks to the careful and devoted work of the Sections, the membership committee, the finance committee, the treasurer, the headquarters office and my predecessors in the presidency of the Institute, the membership is strong, and, as shown by the treasurer's report, the financial condition of the Institute is sound. The year ahead may offer difficult problems in these matters, but, if the long-continuing conduct of the Institute carries any prophecy for the future, these problems, while difficult, will not be hopeless of solution.

I have faith that all of us in co-operation cannot only maintain the membership and the splendid financial condition of the Institute, the excellent character of its publications and the high type of papers presented at its meetings but even somewhat extend the usefulness of the organization to the membership. To this end the administrative officers look to the membership to make known their desires for the progress of their association.



Electrical Precipitation

By WALTER A. SCHMIDT
MEMBER AIEE

EVALD ANDERSON
NONMEMBER AIEE

Probably the most familiar use of electrical precipitation is in the removal of dust particles from air. Nevertheless, the method has a variety of other useful applications in industry, such as the recovery of valuable materials from waste gases, or the cleaning and preparation of gases for subsequent use. The evolution and application of electrical precipitation are reviewed briefly here.

AS EARLY as 1771, G. Beccaria recorded observations on electrical discharges through smoke-filled gases[1] but the experiments of Hohlfeld, in Germany, about 1824, and Guitard, in France, about 1850, who each independently discussed the electrical precipitation effect on suspended matter in gases, are better known. Hohlfeld[2] electrified points in a jar filled with fog and saw the fog particles precipitate on the side of the jar and disappear, and Guitard[3] made similar observations on tobacco smoke.

These early experiments were largely a part of the investigation of general electrical phenomena. About 1880, however, Oliver Lodge in England became interested and investigated different means for cleaning fume-laden gases. Starting with Lord Rayleigh's experiments on the cleaning action of a temperature gradient about a heated metal rod in a dirty gas, and then turning to electrical action he rediscovered the Hohlfeld and Guitard effect. Lodge[4,5] (later Sir Oliver Lodge), however, carried the experiments further and with Walker developed and built the first electrical precipitator at the Dee Bank Lead Works.

The precipitator was not a success, however, partly because the fume chosen was one of the most difficult to precipitate, and partly because the only high-potential source of electrical energy available was the electrostatic generator, which had only a small current capacity. Had he chanced to make his first trial on conducting particles like sulphuric acid mist as later did Cottrell, the story might well have been different. To Sir Oliver Lodge, therefore, should go the credit for having been the first to discover independently electrical precipitation in the laboratory and carry it forward to industrial application.

In Germany, Moeller's "electrofilter," patented in 1884, apparently was never used, and after the unsuccessful attempt of Oliver Lodge to precipitate lead fume, little, if anything, was done in this field for many years. About 1900, Exum P. Lewis, professor of physics at the University of California, whose discovery of the so-called "afterglow" in nitrogen and other electrical effects in gases attest his interest in this field, inaugurated a course in electrical discharge through gases, where one of his lecture demonstrations was a repetition of the Hohlfeld experiment. Among his colleagues and students were Frederick Gardner Cottrell, professor of physical chemistry at the same university, and J. G. Davidson, later professor of physics at the University of British Columbia. One of Doctor Davidson's research problems under Professor Lewis was the motion and precipitation of ions and charged particles in an electric field, where the primary charging action took place in a stage separate from the precipitating action.

Professor Cottrell had become interested in the precipitation of sulphuric-acid mist, which was becoming a serious problem in some industries. After experimenting with centrifugal methods, he turned to the principle described by Hohlfeld and just then being investigated by Professor Lewis and his students. Professor Cottrell realized that a better source of high potential electrical energy was necessary, and adopted the mechanical rectifier and a-c transformer to provide the required high-potential unidirectional impulses. He also recognized that the simplest and nearly always the most effective method was to charge and precipitate the particles in a single stage by the same field and in the same space. He used this principle in the first commercial and really practical electrical precipitator, which he built at Selby, to precipitate sulphuric-acid mist, and which, incidentally, still operates. The two-stage method, in which the particles are charged and precipitated in separate fields or stages, proved less generally applicable, even though it has certain advantages in specific instances.

Professor Cottrell's next commercial precipitator was one for the collection of zinc and lead fume. But despite his fairly adequate electrical equipment, this problem again baffled the investigator, as it had Sir Oliver Lodge many years earlier. The theory of electrical precipitation deals not only with simple electronic carriers in metals and gases or fairly simple ions in liquids, or with electromagnetic effects in space, all of which may be analyzed theoretically. It deals also with charged material particles in gases (as differentiated from electrons and liquid ions), whose behavior is so greatly affected by their environment and immediate previous history that their behavior is far less easily predicted. Lead and zinc fume are extreme examples of these unpredictable electricity carriers, and it was not until many years after Cottrell's experiments that Wolcott[6] discovered the reason for the failure of both

Written especially for ELECTRICAL ENGINEERING. WALTER A. SCHMIDT is president and general manager of the Western Precipitation Corporation, Los Angeles, Calif., and EVALD ANDERSON is technical director of the Western Precipitation Corporation and consulting engineer for the Research Corporation. Mr. Schmidt studied chemistry at the University of California, receiving the degree of bachelor of science there in 1906. Following his graduation he held various positions until he became an engineer for the Western Precipitation Corporation in 1909. He became general manager in 1911. Mr. Anderson, a native of Sweden, also studied chemistry at the University of California and received the degree of bachelor of science in 1913. He has been successively physical chemist, research engineer, and technical director of the Western Precipitation Corporation.

1. For all numbered references, see list at end of article.

Lodge's and Cottrell's lead- and zinc-fume precipitators. Because of the complex nature of its electric carriers, electrical precipitation belongs really more to applied physics than to electrical engineering.

Walter A. Schmidt, one of Professor Cottrell's students, undertook to apply the process to the precipitation of cement-kiln dust at temperatures often exceeding 500 degrees centigrade.[7] Here neither the pubescent electrode previously used in cold gases, nor the serrated mica electrode used with acid mist, was practical. Out of this work came the edge-and-fine-wire discharge electrode, perhaps the greatest improvement in the art since Cottrell's pioneering work.[8]

While the general superiority of Cottrell's single-stage precipitator still was acknowledged these early investigators were fully aware of the special usefulness of two-stage precharging precipitators. Thus Schmidt patented the so-called "follow up treater," which patent discloses practically every kind of two-stage precipitator so far tried in practice, as well as many more not yet tried.

The need by industry for the process was so great that there was hardly ever an opportunity for the ordinary development program. Large $100,000 precipitators had to be designed and built with no more than laboratory tests as guides, but so secure was the foundation on which they were based that there were very few failures. Since then, the organizations that have continued the process both in the United States and in Europe have carried on continuous research and development work, but frequently their engineers find their "new" discoveries fully described in papers by those early investigators.

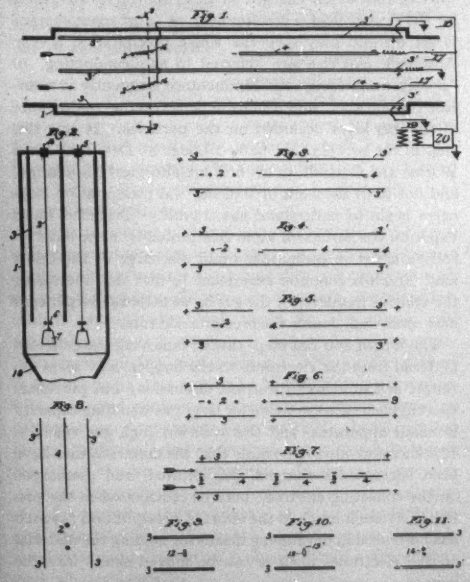


Figure 1. Diagram of a two-stage precipitator, taken from a patent drawing

Figures 1 and 2 (of this figure) show plan and elevation, respectively, of horizontal plate precipitator with ionizing or charging electrodes (2) in the first stage and precipitating electrodes (4) in the second stage

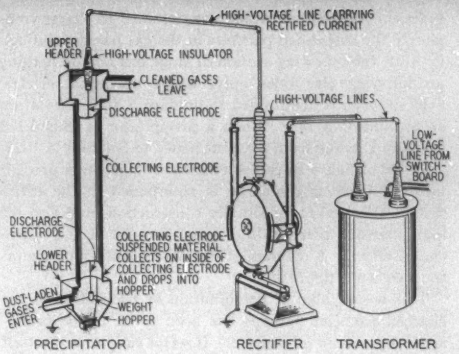


Figure 2. Diagrammatic representation of a Cottrell precipitator

This is a "single-stage pipe precipitator" with a "discharge electrode" serving both as charging and precipitating electrode, shown energized from transformer-mechanical-rectifier power unit

General Principles

In order to remove suspended particles from a gas by the electrical precipitation process the following steps are necessary:

1. Charging the particles by means of gaseous ions or electrons.
2. Precipitating or transporting the charged particles through the gas to the collecting electrode by the force exerted on the charged particles by the electric field.
3. Discharging the charged particles.
4. Removing the precipitated material from the electrode, to a suitable receptacle.

The ions or electrons required to charge the particles may be obtained in different ways, as from flames, radioactive disintegration, or friction, but the only important practical source is the corona discharge in a gas, and ordinarily the discharge is maintained in the gas carrying the suspended matter. The rate and extent of the charging processes by ions of this type have been investigated extensively,[9,10] although there is still much to learn about them.

Both the maximum charge and the rate of charging depend on the size of the particle, the ion concentration, and the strength of the electric field, and, as the speed of a charged particle in the electric field depends on its charge, precipitation engineers strive to secure the maximum number of ions on every particle.

In the so-called precharging or two-stage type of precipitator, one section or stage has a corona field in which

sufficient gaseous ionization is maintained to charge completely the suspended particles in the gas passing through it, while the following section or stage has nondischarging precipitating electrodes only, where maximum electric field strength is maintained to produce a high translation or precipitation rate. Such a precipitator is illustrated in figure 1, taken from a patent issued to Schmidt in 1920.

In the ordinary so-called ionizing or single-stage precipitator, the corona discharge is maintained in the entire field. This makes for simpler construction, and also for high-intensity precipitating fields, because of the space-charge effect. A diagram of such a single-stage precipitator is shown in figure 2.

This second step of precipitation or translation of the charged particles perhaps has been given undue prominence by almost all writers. It seems simple, lends itself to mathematical treatment better than the other equally important steps in the process, and the average reader can get the impression from some published accounts of electrical precipitation theory that this step is the essential feature. In calculating this rate of precipitation, one ordinarily determines or assumes the number of charges on a particle of a given size and calculates its speed in the electric field between the electrodes of the precipitator, assuming Stokes' law for the motion of spherical particles in still gas. The electric field may be either the simple electrostatic field in a precharging or two-stage precipitator, or the more complicated space-charge field in the single-stage precipitator. Such calculations give velocities of from 1 to 60 centimeters per second for particles of from 0.1 to ten microns in ordinary precipitation fields, but the uncertainty of the assumptions makes these values equally uncertain.[9] Actually the precipitation, or translation rate, may be of minor importance in considering the real problem of separating ordinary uncharged suspended particles from the gas and delivering them into a dust hopper or receptacle.

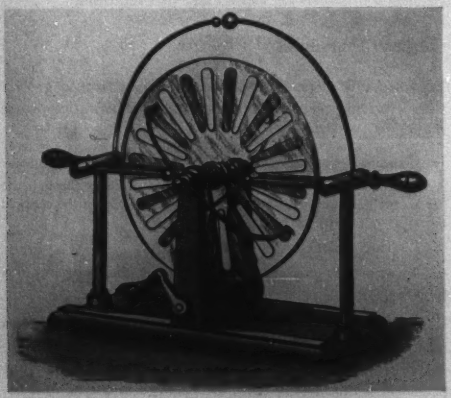


Figure 3. Electrostatic generator as used by Lodge

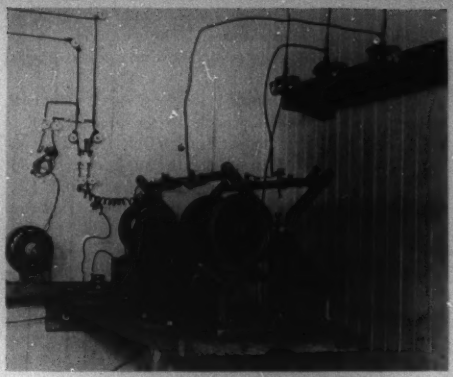


Figure 4. Cottrell's early laboratory rectifier

The third step in the process, that of discharging the charged particles at the collecting electrode, often is the one which actually determines the rate of precipitation. If the electric charges cannot be delivered to the collecting electrode as the charged particles are transported there by the electric field, a counter field, or "dust space charge" is set up and may stop the whole precipitation action. Although particles are referred to as "conducting" or "poorly conducting" the conductance frequently is a surface phenomenon, and usually depends on the conductance of the gas layer occluded on the particles. It was this step in the process that baffled Lodge at Dee Bank Lead Works, and Cottrell, in his first metallurgical installation, and not until the work of Wolcott[6] did precipitation engineers begin to understand the trouble. Occluded water vapor on the surface of a particle probably is the most effective agent in promoting rapid discharge of the "dust ion," and it is common experience to find that increasing the relative humidity of the gas by as little as five per cent may more than double the precipitation rate.

The fourth and last step, that of removing the collected material from the electrodes to the hopper, may seem too simple and obvious to warrant discussion; but precipitation engineers always strive for large gas-handling capacity in small apparatus, and this calls for high gas velocity. It is therefore always possible that the materials that have been successfully charged, precipitated, and discharged on the collecting electrode may be redispersed in the gas. For this reason much of the effort of precipitation research has been used in developing means for holding the material on the electrodes until it can be moved safely into the hopper.

Chemical Activity in Electrical Precipitators

Although the main effects in the electrical precipitation process, that is, separating suspended matter from a gas,

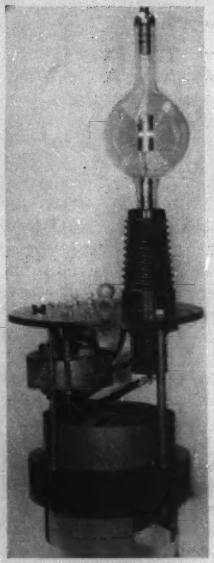


Figure 5. Cottrell transformer, with case removed, and its associated electron-tube rectifier

may belong in the domain of physics, the process is made possible by gaseous ionization, which, if not a chemical process, is at least closely associated with chemical change. Thus, the recombination of gaseous ions may in itself be a step in a chemical process, and the light emission accompanying the corona discharge may serve also to activate chemical changes. This chemical activity associated with the corona or silent discharge has interested investigators for some time. In 1879 Berthelot[11] discussed his own and earlier work on the effect of such discharges in a number of different gases, and more recently Lind[12] summarized the various theories that have been advanced for explaining this effect. Such chemical activity therefore must be associated with electrical precipitation in almost all gases. The proportion of the total electrical energy used for ionization actually transformed into chemical energy is so small, however, that unless the new compounds that are formed have some striking characteristics it is often difficult to prove their existence.

When the corona discharge takes place in air, compounds of oxygen and nitrogen are formed; oxygen molecules and atoms combine to form ozone, and nitrogen combines with oxygen to form nitrogen oxides. However, the ozone formation predominates, and partly for this reason and partly because this reaction is important commercially it has received the most attention. One of the earliest investigators in this field was Warburg,[13] in Germany, who published accounts of his work on ozone formation in the corona discharge as early as 1902. In the United States, Anderegg[14] and co-workers investigated the ozone formation in pipe "precipitators." In the early twenties Anderson investigated ozone formation in a precipitator used for purifying the ventilating air in an office building, and later Mierdel, in Germany, carried out an extensive series of experiments with a great number of different electrode arrangements.

It thus was established early that the amount of ozone formed is proportional to the corona current, is a function of the area of the electrode surface, and that no ozone forms in an ion-free electrostatic field where there is no corona. Investigators that were interested in increasing the ozone production of the so-called ozonizers discovered, for example, that increasing the frequency of the electric current accelerates the reaction, but that water vapor retards it.

The precipitation engineer thus has had the necessary data on ozone formation in precipitators treating air or oxygen, but has not been so fortunate in having data on what to do with the ozone. One school of physiologists and air-conditioning engineers has maintained, and still does maintain, that small amounts of ozone are highly beneficial and make ordinary air similar to the invigorating air in the mountains, or to the air after a thunderstorm on a muggy day. Another school has maintained that ozone is one of the most poisonous of gases, being in the same class as arsene and hydrocyanic gas. A like controversy also goes on regarding the physiological effect of ions in air.

Over 20 years' experience with, and exposure to large concentrations of ozone in closed laboratories forces the authors to conclude that either they and their co-workers are abnormally tough and ozone-resistant individuals, or some of the data on the toxicity of ozone are slightly exaggerated.

Recent data on the use of ozone in refrigerated storage[15] indicate that ozone in concentrations of less than one part per million has no harmful or disagreeable effects on the men exposed to it during working hours. Nevertheless, there seems to be no conclusive proof of the highly beneficial effects claimed by some of the manufacturers of ozonizers, even though Plank, of Karlsruhe, in a recent article reported that certain strains of molds and bacteria become "ozone acclimatized," and then grow faster in ozone-rich air than in ordinary air. This confusion of thought is strikingly exemplified today in some of the larger cities, where manufacturers stress the grave danger of even minute quantities of ozone in ventilating air, while others promote the sale of ozonizers for getting large quantities of ozone into this same kind of air.

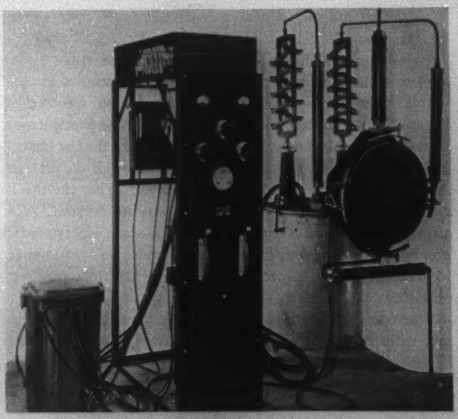


Figure 6. Standard transformer-rectifier set

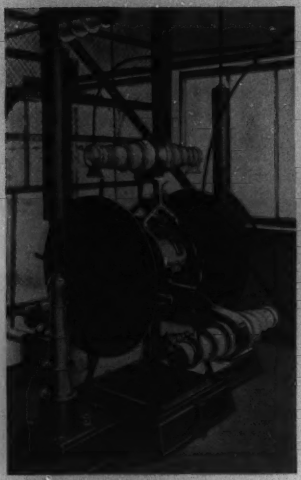


Figure 7 (left). A three-phase mechanical rectifier

Figure 8 (middle). A typical small electrofilter used for sampling

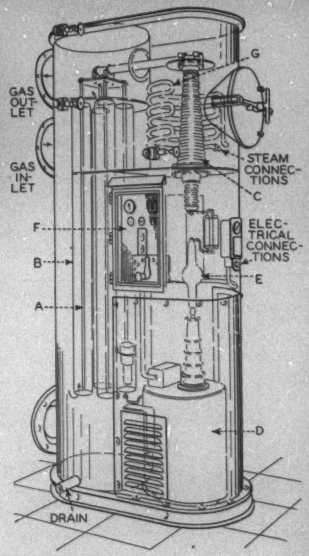


Figure 9 (right). A small single-stage four-pipe precipitator

A—Charging and precipitating electrodes
B—Receiving or collecting electrodes
C—Insulator and bushing supporting receiving and collecting electrodes
D—Transformer
E—Half-wave electron-tube rectifier
F—Control board
G—Steam coil for heating insulator compartment, to prevent condensation

A certain amount of corona current is necessary to charge the dust particles in electrical precipitation, but the electric field for precipitating these particles can be established either with the ion-free electrostatic field of the nonionizing electrodes or with the space-charge-conditioned field of the ionizing electrodes. Therefore, if large amounts of ozone are required, a single-stage ionizing precipitator is used with the maximum amount of current, or with dielectric-covered discharge electrodes. Where minimum ozone is desired, a two-stage precipitator is employed with the ionizing electrode in the first or charging stage, of such size as to give just enough current to charge the particles, and of such type as to give the minimum amount of ozone per unit of charging current. An alternative method is the use of a single-stage electrostatic precipitator with such discharge electrodes and voltage as to give only enough corona for charging the dust or other particles.

The common method of recording ozone formation in precipitators is as concentration in parts per million. This is not a very satisfactory method, however, since it really is only a measure of dilution. A more exact measure is the amount of ozone formed per unit of current. Here, too, because the reaction of ozone formation is a reversible one, the net rate of ozone formation decreases from a maximum value at the beginning, when no ozone is present, to zero in a closed vessel, in which the maximum concentration has been reached at equilibrium. At low concentration, such as used in ordinary electrical-precipitation practice, where large volumes of air are passed by the ionizing electrodes, the ozone formation may vary from 0.1 to 10.0 milligrams per minute per milliampere (equivalent to mols per coulomb). The resulting ozone concentration then may vary from 20,000 parts per million at near equilibrium in a closed vessel, to one part in 400 millions or more in a properly designed precipitator.

Electrical Equipment

The electrical engineer probably is interested chiefly in the electrical machinery used for producing the high-potential electricity in the process. As already mentioned, one of Cottrell's important contributions was his adaptation of the mechanical rectifier and high-voltage transformer for electrical precipitation.

The combination of mechanical rectifier and transformer still is the most common source of power for precipitators. However, other means of rectification, such as the hot-cathode electron-tube rectifier, have been used for many years, and high-voltage a-c generators, such as the Girvin generator also have been tried. But the all-important factor in precipitation still is the nature of the particles in the gas, and almost any source of high-potential unidirectional electrical impulses that produce ions and high-intensity electrical fields serve equally well; so that first cost and operating expense, rather than wave form and other electrical characteristics, have been the primary consideration.

In figures 3, 4, 5, 6, and 7 are shown pictures of some of the electrical equipment used in the process, from Cottrell's early laboratory rectifier and Lodge's electrostatic generator to the electron-tube and mechanical-rectifier equipment of today.

Types of Precipitators

The essential parts of any electrical precipitator or electrofilter, are an ionizing electrode, with its opposing "receiving" electrode, for producing the gas ions and electric fields necessary for the rapid charging of the suspended particles; and the precipitating electrode for producing the electric field necessary to transport the charged particles and to hold them on the collecting electrode until they can be removed to the hopper or receptacle. In the so-called precharging or two-stage precipitator, these parts are separated so as to give an ionizing or charging section and a precipitating or collecting section. In the more common so-called ionizing or single-stage precipitator the fields are combined, and the single set of high-voltage electrodes serve both for charging and for precipitating.

A great many different types of precipitators have been described and used. These differ chiefly in the details of the receiving or collecting electrodes, which may be cylinders or pipes, plain or corrugated plates, special pocket plates or screens and rod curtains. In the last type the gas may pass either parallel to the receiving and collecting electrodes or through them.

Precipitator units vary in size even more than in type. The size ranges from the small gas-sampling electrofilter, handling one or two cubic feet of gas per minute to the large rod-curtain unit for cement-mill or smelter gases, with a capacity of 100,000 or more cubic feet of gas per minute.

Figure 8 shows a Western Precipitation Corporation sampling electrofilter with its electron-tube rectifier set, useful in determining the dust, fume, or mist concentration in gases. Its capacity at over 99 per cent efficiency is about one cubic foot per minute. Figure 9 shows a Research Corporation small pipe precipitator with built-in power unit. This particular unit handles about 200 cubic feet per minute at an efficiency of over 99 per cent. Figure 10 shows a Western Precipitation Corporation tar precipitator, with "Unitranset" power unit, which cleans from 5,000 to 10,000 cubic feet per minute of illuminating gas. Figure 11 shows a diagrammatic sketch of a Western Precipitation Corporation precharging precipitator for cleaning about 50,000 cubic feet per minute of cement kiln gases.

Air-Cleaning Precipitators

Electrical precipitation has found its major application in the more difficult gas-cleaning problems in industry, such as the recovery of valuable materials from waste gases, the prevention of nuisances, and the preparation of gases for subsequent use. In these applications there have been frequent demonstrations of the fact that suspended particles, either liquids or solids and irrespective of size, can be precipitated from gases so completely that only the most minute traces remain. The extensive use of electrical precipitation, for example, for complete removal of arsenic and other catalyst poisons in contact sulphuric-acid manufacture depends on this characteristic. These applications may go somewhat beyond the dust-removal requirements in the relatively new field of air conditioning, but experience with existing systems indicates increasingly the need of refinements in this direction, and of greater air cleanliness than is obtainable by present methods. Similar situations usually have been responsible for the growth of electrical precipitation to its present status, and when the history of its development for this application is written it probably will be a repetition of that of other applications, which have been so extensively de-

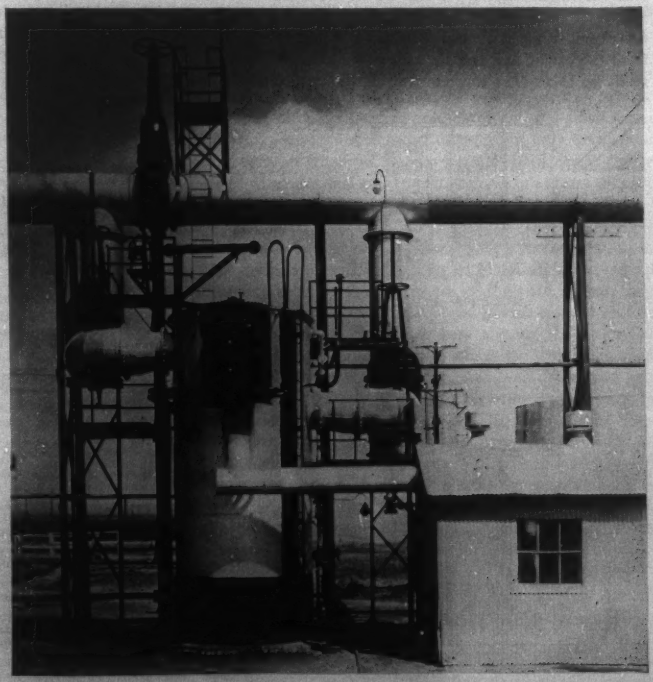


Figure 10. A tar precipitator that cleans from 5,000 to 10,000 cubic feet of illuminating gas per minute

scribed in the literature. Where it was necessary, for example, to control the "dust space charge effect" to make Lodge's initial industrial application practical, it may be necessary in air-conditioning applications to control ozone formation before the other desirable characteristics of electrical precipitation can be utilized fully.

An interesting description[16] of a recent installation of an air-cleaning precipitator was given in ELECTRICAL ENGINEERING for November 1937.

One of the earliest applications of electrical precipitation for air conditioning was in connection with gas masks, during the World War. Lamb[17] and his co-workers developed a small precipitator with tubular collecting electrodes from four to six inches long and energized from dry batteries and induction coils. This precipitator removed such toxic suspensoids as diphenylchlorarsene, which were not removed by the regular gas mask.

Figure 12 shows a precipitator that was operated in 1923 on the ventilating system of a large office building in a central California town. During that period ozonizers were even more popular than now, and one of the objects of the use of that equipment was to determine whether the ozone, incidental to the operation of a precipitator for cleaning the air, would make the cooled but rather humid air from the air washer more agreeable. The precipitator was the single-stage type, and the ozone formation was varied by changing the current; but the occupants of the offices failed to notice any particularly exhilarating effect from the ozone, and the air entering the building was already so clean that the removal of the small amount of impurities present did not justify the continued operation of the equipment.

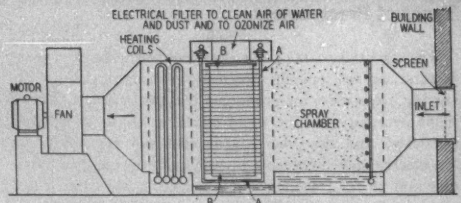
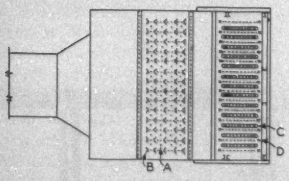


Figure 12. Diagram of a single-stage plate precipitator as operated on a ventilating system

A—Wire discharge electrodes
B—Plate precipitating electrodes
Both *A* and *B* are placed between sprays and tempering coils in a standard air washer

Until physiological chemists and ventilating and air-conditioning engineers agree on the function of ozone, the precipitation engineer therefore will have to follow the fashion of the day. For those who "believe" in ozone, he will design precipitators to produce the maximum ozone for a given cleaning effect, while for those who believe ozone harmful, he will design precipitators to give the desired air cleanliness while producing so little ozone as to be undetectable in the treated air by even the most sensitive analytical methods now in ordinary use.



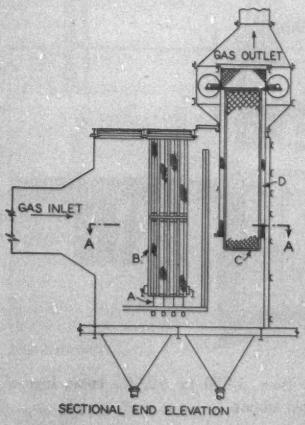


Figure 11. Sketch of a precharging precipitator used for cleaning about 50,000 cubic feet of cement-kiln gases per minute

A—Wire ionizing electrodes in the first stage
B—Screen plate receiving electrodes in the first stage
C—Screen plate precipitating electrodes in the second stage
D—Receiving electrodes in the second stage

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The Engineer and Trends in Economic Thought

By FRANK B. JEWETT
FELLOW AIEE

A leader in research and past president of the Institute makes several observations on the world of economics and the engineer's relation to it

ALTHOUGH the exact wording of the title which I have chosen for this talk may be a little different from any I have used previously, the subject matter is not essentially new. In common with many of you, I have for years, when suitable occasion offered, voiced my belief about a different position and responsibility for engineers than that which society has in the main accorded us, or in fact than that we have accorded ourselves.

Ten or fifteen years ago this was a pleasant extra-curricular activity which not many took very seriously. Now, however, times have changed and I must admit that it is not without trepidation that I again venture into the field. We engineers and scientists, whose training and experience has been largely among the exact sciences, and who deal with problems capable of more or less quantitative solution, are, I think, likely to be irked rather than entertained by a subject which leaves so much latitude for speculation and display of individual preference as does that of the government of society. Nevertheless, we cannot escape an increasing awareness of the fact that in recent years the world outside the totalitarian states is pointing a questioning if not an accusing finger at the engineering profession and its works.

Many Economic Experiments Are Not Scientific

One of our present embarrassments lies in the fact that in the last decade it has suddenly and without real understanding of the scientific method, taken some of our protestations and arguments at more than their face value and has attempted to apply them wholesale far beyond the limits of possible successful operation.

Not only here in the United States but to a greater or less extent in every other country in the world, one of the most ghastly hoaxes imaginable has been perpetrated on society. I refer to the flood of social, economic, and political adventures which have been launched under the banner of "scientific experiments."

That they have been and are experiments, at least so far as this generation is concerned, albeit many of them are hoary-headed failures of the past, no one can deny. That they are scientific is, however, a travesty on everything which we of fundamental or applied science recognize in the term or as the underlying basis for our success in discovering and utilizing the hitherto hidden forces of nature. Over the years we have proclaimed the power of the scientific method and our successes in every domain of fundamental and applied science have been proof of our assertions. With evidence of these achievements in the material world everywhere apparent and with the phrase "scientific experiment" already an accepted byword and an alluring slogan, it was, I suppose, but natural that when existing concepts of social, political, and economic orders began to crack, the slogan should be seized upon by proponents of every new theory and accepted unquestioningly by the rank and file of society. Almost without exception, however, the social and political sorties which have been staged under this stolen banner have been without scintilla of justification of what we of science and engineering understand as the scientific method. To us a scientific experiment is one which under controlled conditions can be repeated at will, and in which but a single unknown factor is involved—or at most a very limited number. It is a method which is never used on a large scale before proved results are obtained on a small scale. It works successfully in our domain not only because of the controls which we impose but also because the things with which we deal are either inanimate or at least without conscious volition.

The charitable thing to say about those who have raised the banner of alleged scientific experimentation in the social and political sectors as justification for radical departures from the experience of the past is that they were ignorant of the fundamental postulates of scientific experimentation. I am not here arguing that many of the social and political things which the world has tried out in recent years should not have been attempted, but I do think it a tragedy of the first order that they were undertaken on an argument so fallacious as that they were scientific experiments. The tragedy lay both in leading vast numbers of people to believe that more could be accomplished than was inherently possible and in violation of another fundamental tenet of scientific experimentation; namely, frank and honest stoppage of an experiment when it is clear that it is going wrong.

Does Science Contribute to the Economic Well-Being of the World?

All that has happened in the last decade has tended unquestionably to bring certain aspects of science and the scientific method under a suspicion which is as undeserved as was the claim of infallibility which preceded it.

Essentially full text of an address delivered at a meeting of the Western Society of Engineers, Chicago, Ill., May 5, 1938, at which time the Washington Award for 1938 was presented to Doctor Jewett "for inspiring and directing scientific research leading to improvements in the art of communication." A biographical sketch of Doctor Jewett appeared on page 83 of the February 1938 issue of ELECTRICAL ENGINEERING.

Under the circumstances, and however unwelcome the task may be of exonerating science and ourselves from these suspicions, we can hardly remain oblivious of the issue that has been raised.

Although the world continues to welcome enthusiastically the material conveniences which the scientist and engineer are conferring upon it, there is an undercurrent of uncertainty and suspicion in present-day public opinion regarding the true social value of many of our technological contributions. To be sure, there is something ironic in the picture presented by a man who is awakened by an electric alarm clock, shaves by choice with an electric razor and with electrically heated water, breakfasts off dishes prepared on electric appliances, is transported to his office in an automobile and by electric trains and elevators, there to transact most of his business by telephone and with the aid of innumerable mechanical gadgets, but who in his spare moment conjures up visions of dangers inherent in an over-reliance upon technological aids and conveniences. But while we may smile at this we cannot close our minds to such influence as that which the motor car has had, not so much upon safety as in the way of increased temptation to crime and moral laxity. Further, the introduction of cheap printing methods and the emergence of radiobroadcasting and talking motion pictures from science, have displaced the lyceum platform and the more substantial literature upon which our forbears depended for intellectual guidance. Evidence is not lacking that the ever-mounting flood of reading matter and predigested information may be diluting the intellectual fodder chosen by great numbers of people. If the first impact of rayon on the textile world, as a substitute for silk, had remained its sole or principal impact, its development would still have been a noteworthy scientific achievement. When, as now, it is mixed with or substituted for all other fibers to the end that cheaper products are available—but products which we sometimes suspect supply less of real value for the customer's money than previously—it is not surprising that thoughtful people may sometimes classify it with other things of science to be questioned. In this recital I should be less than gracious if I made no reference to the telephone and telegraph, which in their ubiquitousness have unquestionably undermined to some extent one of the best of ancient arts—that of letter writing.

I would not, however, ask that you take my words alone. Let me quote from a recent article by Gilbert Murray in which he weighs the pros and cons of technology.

"In this machine age man has had to pay a heavy price for the help given him by his machines. Take a well-fitted modern observatory; a telescope with a very large lens, a clockwork arrangement enabling it to follow exactly some particular part of the sky, a fine photographic apparatus to record the light of the stars, even stars quite invisible to the eye. A man looks at the photograph and discovers on it a new star. A great achievement, but due chiefly to the machine, not the man. Such a man is not using nearly as much mind, as much thought and brain power, as an ancient Greek or Chaldean astronomer who with no instruments at all observed and calculated nearly right, if not quite right, the main movements of the heavenly bodies. Think of a stupid fat man driving fast in a beautiful motor car which he does not understand; or the millions of clerks who are carried blindly to their work every day by train or bus: they are not using nearly as much intelligence as the man of a hundred years ago, walking on his own legs, looking about him, noticing plants and trees and birds. No doubt immense skill and brain power have gone to making the instrument—the telescope, the motor car, or steam engine; but the instrument, when made, actually diseducates the user. It enables him to do what he wants, or get where he wants, almost without using his mind or brain or limbs at all. And if he need not use them you may be sure he won't use them."

I have quoted this to illustrate a point of view commonly expressed and not because I agree wholly with Murray. I think the very point he makes could be turned against him.

Economic Discontent Is Not New

Before going any further in our survey it may be well to reassure ourselves with the reflection that anxiety concerning moral decadence following technological advances is no new thing peculiar to our day and age. We all know that it has long been customary to sigh for the "good old times." I recall having once read of a Chaldean tablet which when deciphered must have astonished its translator with its decidedly modern flavor, for it bore the following message:

"We have fallen upon evil times. Public officials are no longer honest and children no longer respect their parents."

Further, one of the most astounding things which a visit to Egypt or a study of the records of archeological exploration there discloses, is the vast record of social and political experiments, successful and unsuccessful, which were tried millennia before Christ was born. One has but to read the story of Akhaaton, the great iconoclastic Pharaoh, 1375 B.C., to sense that he would have been a valiant leader in many a modern adventure.

Coming to a somewhat more recent age, many of you doubtless have seen the statement quoted recently by Sir Josiah Stamp:

"Travelling in these Coaches can neither prove advantagious to Men's Health or Business; For, what advantage is it to men's Health, to be called out of their Beds into these Coaches, an hour before day in the morning, to be hurried in them from place to place till one hour, two or three within night; insomuch that after sitting all day in the Summer time stifled with heat, and choked with dust; or the Winter time starving and freezing with the cold, or choked with filthy Fogs, they are often brought into their Inns by Torchlight, when it is too late to sit up to get a Supper; and next morning they are forced into the Coach so early, that they can get no breakfast. What addition is this to Men's Health or Business, to ride all day with strangers, oftimes sick, ancient, diseased Persons or Young Children crying. . . . Is it for a Man's Health to travel with tired Jades. . . .

"For passage to London being so easie, Gentlemen come to London oftener than they need, and their Ladies either with them, or having the Conveniences of these Coaches, quickly follow them. And when they are there they must be in the Mode, have all the new Fashions, buy all their Cloaths there and go to Plays, Balls and Treats, where they get such a habit of Jollity, and a love to Gayety and Pleasure, that nothing afterwards in the Countrey will serve them."

Because it antedates the present by just a hundred years, perhaps the most interesting of all the expressions

of foreboding are some passages to be found in Macaulay's essay on "Southey's Colloquies on Society." Speaking of Southey's opinion of the manufacturing system, Macaulay says:

"There is nothing which he hates so bitterly. It is, according to him, a system more tyrannical than that of the feudal ages—a system of actual servitude, a system which destroys the bodies and degrades the minds of those who are engaged in it. He expresses a hope that the competition of other nations may drive us out of the field; that our foreign trade may decline; that we may thus enjoy a restoration of national sanity and strength."

Time does not permit quotations of any of Southey's own arguments against the changes of his time. Macaulay, of course, takes emphatic exception to Southey's views, and in a passage which for eloquence and appropriateness to our own situation it would be difficult to excel, he says:

"The present moment is one of great distress. But how small will that distress appear when we think over the history of the last forty years; a war, compared with which all other wars sink into insignificance; taxation such as the most heavily taxed people of former times could not have conceived; a debt larger than all the public debts that ever existed in the world added together; the food of the people studiously rendered dear; the currency imprudently debased, and imprudently restored. Yet is the country poorer than in 1790? We firmly believe that, in spite of all the misgovernment of her rulers, she has been almost constantly becoming richer and richer. Now and then there has been a stoppage, now and then a short retrogression; but as to the general tendency there can be no doubt. A single breaker may recede, but the tide is evidently coming in."

And then continues in the oft-quoted passage which, as you may remember, was written in 1830:

"If we were to prophesy that in the year 1930 a population of fifty millions, better fed, clad and lodged than the English of our time will cover these islands; . . . that machines constructed on principles yet undiscovered will be in every house; that there will be no highways but railroads, no traveling but by steam; that our debt, vast as it seems to us, will appear to our great grandchildren a trifling encumbrance which might easily be paid off in a year or two—many people would think us insane. We prophesy nothing; but this we say: if any person had told the Parliament which met in perplexity and terror after the crash in 1720 that in 1830 the wealth of England would surpass all their wildest dreams; that the annual revenue would equal the principal of that debt which they considered as an intolerable burden; . . . that London would be twice as large and twice as populous, and that nevertheless the rate of mortality would have diminished to one-half of what it then was; . . . that stage-coaches would run from London to York in twenty-four hours; that men would be in the habit of sailing without wind, and would be beginning to ride without horses—our ancestors would have given as much credit to the prediction as they gave to Gulliver's Travels. Yet the prediction would have been true. . . ."

Were he here today I doubt not that Southey would certainly have been delighted with many of the experiments in government which we are witnessing, for, according to Macaulay, Southey viewed government as a "jack of all trades."

". . . . . architect, engineer, school-master, merchant, theologian, a Lady Bountiful in every parish, a Paul Pry in every house, spying, eavesdropping, relieving, admonishing, spending our money for us, and choosing our opinions for us. His principle is, if we understand it rightly, that no man can do anything so well for himself as his rulers, be they who they may, can do it for him, and that a government approaches nearer and nearer to perfection in proportion as it interferes more and more with the habits and notions of individuals."

How close home this strikes! Macaulay counters with a proposal which also has come to possess a singular familiarity:

"It is not by the intermeddling of Mr. Southey's idol, the omniscient and omnipotent State, but by the prudence and energy of the people, that England has hitherto been carried forward in civilization; and it is to the same prudence and the same energy that we now look with comfort and good hope. Our rulers will best promote the improvement of the nation by strictly confining themselves to their own legitimate duties, by leaving capital to find its most lucrative course, commodities their fair price, industry and intelligence their natural reward, idleness and folly their natural punishment; by maintaining peace, by defending property, by diminishing the price of law, and by observing strict economy in every department of the State. Let the Government do this: the People will assuredly do the rest."

In spite of Macaulay's complacent reassurances, I doubt that any of us fail to recognize in the present situation, both at home and abroad, the existence of forces of unrest which are far deeper than could arise merely from discordant political shibboleths. Many if not most of these trace back to the doorstep of the engineer and scientist because it is around the things of their creation that the maelstrom surges most violently.

Expanding Technology Necessitates Better Planning for the Future

By creating cheap and abundant mechanical power and the countless industrial operations made possible by it, we have let loose social forces of stupendous magnitude with which the world has not, as yet, had sufficient experience to be certain even of their direction, let alone their magnitude.

Our present difficulty, as I see it, is not that we scientists and engineers have produced too many things too fast, and that there should be a holiday in applied science, but rather that we, in common with the world at large, have failed to take seriously enough the matter of foreseeing and providing for the more important social consequences of our material achievements. If this is, as I believe it to be, a valid criticism of social action during the past 150 years, then we of science and engineering, more possibly than most other groups, have something to account for. When, 25 or 30 years ago, I began to voice questionings of this kind and to argue for a broader conception of the engineer's function than I had been trained to, the answer which I received more commonly than not, even in educational institutions, was that the primary function of an engineer was to confine himself to the production and operation of the things of applied science, and let others worry about the social and political adjustments. I thought then, as I think now, that any argument along this line involves a fallacious assumption, namely, that nontechnical people, in addition to whatever competence they may have in their own fields, can be assumed to have as much competence about applied science instruments as those who create these instruments.

After saying this, let me hasten to add that I would not

have you for a moment think me an advocate of turning over the operation of social or political matters to scientists or engineers. In my judgment, and speaking as one of the breed, I think that as a group, in which however there are many notable exceptions, we are probably less qualified than other groups to handle problems so far removed from the realm of controllable things with which we are accustomed to deal. All that I am trying to express is that we as scientists and engineers, both in our current functioning and in setting up the education of those who will follow us, should have a somewhat different concept of social responsibility than in the past. Further, that society generally, since it must continue to live with the things of applied science, will be well advised if it seeks seriously to find a way of enabling us to apply such talents as we may possess a bit beyond the realm of creating new instrumentalities.

We, and particularly we here in America, are all entirely familiar with what applied science has already done in bringing not only the so-called comforts of life, but also many of its luxuries as well, virtually within the reach of every one. In fact we have come so close already to realizing the age-old dreams of plenty that mass patience breaks down even at the prospect of small delays or deprivations. So far as I can see, and while I no more than others can forecast the future in detail, there is no present reason to believe that we are nearing the end of the stream of new things. If this is so then our problems of social adaptation will continue with us for an indefinite period. Under such circumstances common sense would seem to indicate the desirability of organizing for the future a bit better than we have in the past. If we do there are I think two factors among others which we must keep always before us: (1) that there are no safe short cuts to a desired goal over untrodden terrain; and (2) that men's sense of values is entirely relative. We human beings are not at all interested in contrasting our present situation with that of our fathers or grandfathers. The only thing which appeals to us is the contrast of our present situation with that of a year or so earlier, or with that of our immediate neighbor.

Economic depressions are not new phenomena, nor are they likely to cease with the passing of the present one. It was not very long ago that hard times meant not only misery but also virtual starvation for multitudes. In the western world at least, the tragic phase of starvation has happily passed but that does not mean that the discontent and suffering of a depression period has been lessened for those involved in it.

Science Is a Vital Factor in the Economic Balance of a Nation

Let us turn now to the question of economic balance and its upsetting—a field in which the results of the engineer's work are unquestionably a major factor. I do not wish to imply that all or even a majority of technology's contributions have raised difficulties concerning industrial assimilation. When we recall the disturbing influences to which our single most fundamental and most necessary industry—agriculture—has been subjected, however, partly by development of improved methods of culture, partly by rapid and cheap transportation with consequent increase in the scope of competition, partly through direct application to the work of the farm of power which must be purchased abroad rather than created at home, and partly through the development of such an industry as that of rayon, which has already usurped a considerable portion of the domestic market for cotton, wool, and linen, we can be pardoned for expressing amazement that adjustments, both national and international, have remained as stable as they have.

Or, turning to the problem of employment, where labor has been geared more and more to machine production and has become correspondingly helpless without the machine's aid, we who have been the creators of machines certainly invite the raising of a none-too-pleasant reckoning with a novel aspect of the law of diminishing returns. Whatever the relief which a more remote future may hold in store for us, we must today, if we are honest, admit the peril of a fundamental danger. In many respects a nation or a society has the characteristics of an individual. With an individual, liability to contract many diseases is in direct relation to the undermining of normal bodily health; so with a nation. Although we here in the United States have not gone nearly so far as many elsewhere in the world, we have nevertheless joined the ranks of those nations whose political and industrial constitutions have become undermined. Such a condition incites a certain morbidity of thought. Like the man who in good health has no difficulty in avoiding the temptations of the "quack," but who through suffering from prolonged illness becomes desperate and yields to the allure of unscrupulous blandishments, we as a nation are facing a type of danger which was nonexistent in more prosperous times.

Here in America, confronted though we are with the same problems that have bedeviled the rest of the world and driven nations over the precipice of despair of themselves, their institutions, and their traditions, we are still blessed beyond all others in many vital things. We have an abundance within our borders of most of the major elements of virile economic life; substantial freedom from the hideous nightmare of impending war; a vast but not too vast population of intelligent educated men and women living in a single ample area; the tradition of centuries of law and government operating in a democratic society not to do things for people but to enable them to do things themselves and best of all, freedom still of thought, inquiry, and expression for the individual with a maximum of opportunity for each to play his or her part with a minimum of imposed restraint and regimentation.

The fact that during the past decade or two we have worshipped numerous false gods and chased many will-o'-the-wisps that seemed to offer us a short cut to the pot of gold at the foot of a rainbow should not cause us to lose our sanity, our sense of proportion, our tolerance of others, or our courage.

In the challenge of the turbulent years ahead, we of science and engineering cannot escape playing a promi-

nent part. Whatever some distant future historical appraisal may say of us and our works, past, present, and future, it must say something, for we *have* created many things that have developed economic, social, and political problems of the first order. I hope it can say something laudatory of our contributions to their solution.

That we will continue in the future as in the past to delve into Nature's unknown and to employ what we find in new things for society to use or misuse, goes without saying. We will do this partly because we are curious, partly because it is our field of adventure in life and partly because as a group we have a deep-seated innate conviction that society will profit by having a greater variety of more goods and more things to lighten human toil and enlarge the sphere of opportunity for enjoyment of life. It cannot be otherwise, for if we did not feel so we would seek adventure elsewhere. We are not scientists and engineers rather than merchants, lawyers, farmers, artisans, or other honorable workers merely for the sake of earning food, clothing, and shelter.

The fact that many of the things we have or will create can be used to the detriment of society as in war, or by criminals, or temporarily in foolish ways not in its permanent best interest is nothing new, and no valid argument against producing new things. One has only to view the vast array of pictorial evidence in the tombs and on the monuments of Egypt which take us back to the beginning of human history to see that it has always been so. Nor can any one deny that slowly through unnumbered millennia the progress of society and of individual freedom has been upward, despite periodic dark ages, and has been most evident in those peoples who were creators of new things. When they ceased to create, the nations they constituted ceased to lead.

Where Does the Scientist Fit Into the Economic Pattern?

It is outside this essentially normal sphere, however, that the great challenge and great opportunity for scientists and engineers exists in the years ahead. It is the challenge and opportunity to contribute something more than we have of our special knowledge and special skills to the solution of intricate economic, social and political problems, many of which arise directly from our work as scientists and engineers.

On the positive side and with rigid adherence to the critical standards we must impose in our work, we frequently can provide valuable information of what can or cannot be expected economically or socially from our creations. Our views applied merely to the obvious outward manifestations of our works may be no better than those of others, and frequently are not so good. What we have—or should have—that others do not possess, however, is real information as to how far and in what way these surface manifestations are likely to be modified by advances in science itself. All of us—at least those of my generation—can recall instances of grave economic, social, and political errors arising out of assumptions as to the future which could have been avoided had knowledge of probable future developments in the possession of the more competent scientists and engineers been brought properly into the picture. That it was not was due either to lack of adequate machinery or a feeling on the part of the men in question that the matter was outside their province.

It is on what might be called the negative side that we may be able to make the greatest contribution to the orderly solution of economic, social, and political problems. We, more than any others, know the power, possibilities, and, above all, the limitations of science and of the scientific method of attack. This is not because we have any superior wisdom but merely because we have been specially trained in the knowledge and technique of science and its arts. We know that the great achievements of science and engineering are never the results of brilliant chance unrelated to previously established knowledge. Irrespective of how radically new they may appear to the uninitiated, they are always direct lineal descendants of what has already been proved. Usually they are not really very great adventures beyond it. To venture further is to become a gambler rather than a scientist or engineer. Even when occasionally for reasons beyond his control the scientist or engineer is forced to go further than prudence dictates, he always injects "factors of safety"—really "factor of ignorance"—and is the first to beat a retreat to firm ground when danger threatens.

Having to operate in a field where Nature's inexorable laws are swift to punish transgressions and cannot be hoodwinked even temporarily, as is sometimes possible in the social and political sector, we are acutely conscious of the dangers inherent in large-scale excursions into untested regions, particularly when many unknown and so uncontrollable variables are sure to exist. We have learned through sad experience the virtue of the old motto about the shortest way home and the value of the succession of small-scale laboratory trials as a necessary prelude to successful large-scale use. It is only through them and the opportunity they afford of unearthing and correcting individual small difficulties and mistaken assumptions which saves us from having them pile up in great failures. It is an axiom in science and engineering that what can be done in a laboratory may be done on a large scale; what cannot be done there cannot be done on a large scale.

Further, we know the amount of time which must elapse in the laboratory stage of any new development before practical application can be undertaken safely. We are prone to emphasize this and the multitude of difficulties to be overcome. Actually both are great, but relative to the corresponding factors in social and economic problems they are few and simple.

Out of all this experience should come in the years ahead an enlarged opportunity to apply it in the social, economic and political fields if in no other way than by influencing sincere men and women to avoid undertakings which in the very nature of things are doomed to failure because of the unknown or uncontrollable factors inherent in them. It is a challenge to us and likewise to our whole scheme of universal education.

Whether we like it or not our world and that of our children will be increasingly shot through with major social problems arising from use of the "gadgets" we create. We, and the society of which we are a part, will fall short if it and we fail to evolve a more orderly method of solution than that of the jungle, merely because we lack the wit and will to apply established knowledge and proved technique to it.

In our plans for a better and more efficient future we need not concern ourselves much about technical education per se. That will take care of itself automatically. The great problem, as I see it, is the education of the general population—those who are not to be practitioners in the field of science, but whose decisions control the current of its application.

The problem is in essence a simple one, although its solution is most difficult, both on account of sheer magnitude and because of past and present errors. It is the problem of indoctrinating the thinking part of the population with a modicum of better understanding of science and its techniques—of its powers and limitations. All that is required is something sufficient to offset the superficial assumptions engendered by outward appearances and to impel men and women to seek advice from those in position to have it and to ponder this advice before acting.

It is something in which we can help and something to which our great foundations can well give attention. Solution need not contemplate implanting much, if any knowledge of the detailed facts of science. It will, however, be likely to do violence to much of current pedagogical theory and practice which has been badly bitten by the bug of unscientific methods masquerading under the banner of science.

My interest in museums of science and industry is grounded in the hope that they in time may add a mite to a better understanding. They are still far from doing all that is possible and their progress will always be limited by the previous understanding of their visitors.

I for one am a confirmed optimist in believing that we can, and will, succeed. I say this with full recognition of the difficulties to be overcome, of the time involved and of the discouragements in the way. If I have learned one thing from forty years of struggle in science and engineering, it is not to expect to reach the promised land by lunch time or over a smooth highway unencumbered by traffic lights or detour signs. These may be irritating and cause us to arrive later than we hoped, but they do insure a safe arrival for us and our children also.

New Equipment to Keep Legislators Cool

RECENTLY completed in the power plant serving the national capitol is the refrigerating machinery shown on this page. Claimed by the manufacturer to be the world's largest single installation of refrigerating machinery for air-conditioning purposes, this apparatus will cool more than 11,000,000 gallons of water per day—enough to air-condition the United States Capitol, the Senate Office Building, and the old and new House Office Buildings.

The compressors are driven by six 1,000-horsepower 6,660-volt 25-cycle synchronous motors, excitation for which is supplied by a 100-kw motor generator set. Pumps, driven by steam turbines, draw condensing water from the Anacostia River through more than half a mile of 30-inch pipe. The water is distributed to the condensers and finally returned to the river by gravity. Similar pumps force the chilled water, at a temperature of 40 degrees Fahrenheit, through 24-inch supply mains to air-condition the buildings and return the warmed water to the coolers; during this cycle the cooling water makes a round trip of more than a mile.

All the cooling equipment as well as auxiliary equipment is contained in a space 120 feet long by 78 feet wide and a net operating height of 16 feet. Interesting side lights: The equipment is so compact that its daily output is equivalent to the melting of a block of ice greater in volume than the space required for the cooling machinery itself. The power plant has a pumping capacity equal to that of a water system supplying a city of more than 200,000 people, allowing the standard of 60 gallons per person per day.

Rural Electrification in England

A review of the present position of rural electrification in England, giving special attention to the economic aspects of electrification in rural areas, and describing a typical British rural electric system

THE PROVISION of public supplies of electricity throughout rural areas is regarded in all progressive countries as an urgent and important necessity for the general welfare. In Great Britain powers have been granted to various authorities covering almost the entire country, and reasonably good progress is being made in extending electric service to the rural areas, as reported in a paper by J. S. Pickles entitled "Rural Electrification," which was read in London before the Institution of Electrical Engineers, December 2, 1937. The term "rural electrification" frequently is misapplied to areas that would be more correctly described as urban or suburban. Throughout the paper the author uses the term "rural electrification" in application to large areas devoted principally to agriculture, and mainly containing only scattered population.

The density of population of a rural area commonly is expressed in persons per square mile. The figure obtained by dividing the known population by the total area is held to be misleading and as giving an erroneous impression of the actual area because many rural areas possibly contain portions of hilly or marshy country that is virtually unoccupied. A safer working figure is obtained by excluding such unoccupied territory and determining the population per square mile of the effective area. As used here such a figure is referred to as the *effective* density of population. For example, in the Dumfries County area, the actual density of population is 55 persons per square mile, but if the mountainous and virtually unoccupied parts are excluded, the effective population is approximately 100 per square mile. A distribution in which one half of the population of the area is in towns and villages and the other half is scattered over the remainder of the area is considered, for convenience of reference, to be a *normal* distribution.

Most of the early engineering difficulties associated with rural electrification in England have been solved satisfactorily against handicaps not ordinarily imposed upon engineers in the United States. British villages are more densely built, with narrower streets; rural highways are narrower and more winding; and the rules of the Board of Trade and the Postmaster General are more restrictive and conservative than are the public utility regulations in the United States. The one major problem that appears to have defied complete solution in England is protection against lightning discharges. Though damage from lightning strokes may be partly mitigated in some rural areas, it still is a very serious trouble to engineers in charge of large interconnected overhead networks. Another remaining problem is that of providing satisfactory protection to the consumer in areas where earthing conditions are poor, but much progress now has been made toward its solution.

"Financial" Engineering Important in England

The principal difficulty in the electrification of rural areas in England does not involve engineering technique, however, but the financial problem of "making ends meet." Successful rural development is a continual struggle on the one hand to keep down the necessary capital cost to a minimum, and, on the other hand, to insure the early and rapid development of revenue. Economy in capital is extremely important, and all means to that end consistent with reasonable reliability of supply must be employed.

At first sight rural electrification might still appear to be a risky financial venture in view of the many miles of mains required and the comparatively high cost of distribution. Fortunately, as regards capital costs, practice has shown that with extensive use of overhead lines and careful design, the total capital cost per consumer can be restricted to a figure not much greater than the corresponding cost for the densely populated areas in which relatively expensive underground cables are necessary. Although there are many apparent difficulties, domestic revenue per customer can be much higher in a rural area than in a town or urban area. This is not because wages are higher, since the contrary usually applies, but is due to several contributory factors. Competition against gas as a heating or cooking fuel is entirely absent, or is not so intense as in urban areas; coal is expensive; there are fewer outlets for the spending of wages; the home is used much more; and the many comforts that can be provided by electricity are more eagerly sought.

Increasing Farm Loads— A Promising Source of Revenue

In any rural area the farms, even on the basis of numbers only, represent a material proportion of the total available consumers. Moreover, farmers own or are responsible for the tenancy of most of the agricultural workers' cottages, and the whole welfare of the countryside revolves around agricultural progress; therefore, no plan of rural electrification can be considered to be successful unless a deliberate attempt is made to obtain the connection of the greatest possible number of farms.

Although it might appear that much has been done already in the extension of electric service to farms, the progress hitherto made really is only a small part of what remains to be done. Completely authentic records of

farm connections are not available, but the following figures are believed to be substantially correct: In 1926, 600 farms connected; in 1932, 4,000; 1936, 25,000; 1937, 30,000. Since in Great Britain there are nearly 450,000 farms and small holdings of over one acre, obviously only a small part of the total is connected to a public supply.

Engineering Features of Rural Systems

The principal part of the large-scale distribution system is a high-voltage network of three-phase overhead lines, operating at 11,000 volts, since that is the highest standard voltage at which lines can be tapped economically for isolated customers. Steel-cored aluminum conductors at present are used extensively. Conductor sizes need not be large, since such lines seldom are deficient in current-carrying capacity, and relief from the possible trouble created by voltage drop can be obtained more economically by the use of automatic tap-changing boosters than by the provision of large conductors.

Table I. Relative Figures for Three Different Systems of Supply, Assuming Equal Lengths of Low-Voltage Distribution Main With Balanced Loading

	Number of Conductors	Relative Capacity	Relative Cost
Single phase	2	1	1
Single phase	3	4	1.26
Three-phase	4	6	1.51

For high-voltage spur lines galvanized steel conductors have been found to be suitable in every way and will withstand snow storms more satisfactorily than many other types. The author urges that, in the interest of economy, all spur lines should be single phase—even in route lengths up to ten miles—in serving only sparsely populated parts of the area. Exceptions should be made only of those lines which ultimately may form parts of the general three-phase network. In towns and principal villages electric supply normally is provided from three-phase low-voltage networks, but in small villages the author strongly advocates extensive use of the single-phase three-wire method of distribution. It is further suggested that all isolated consumers such as farms and country houses should be supplied by single-phase 11,000-volt tappings.

In villages the two-wire single-phase system is satisfactory for small groups of houses up to, say, ten in number. For larger groups forming small villages having up to 50 houses, the single-phase three-wire system is recommended, with 230 volts between each phase wire and neutral and 460 volts between lines. Table I shows a comparison of alternative systems of supply assuming equal voltage drop, and shows that the single-phase three-wire system costs only 26 per cent more than the two-wire system, but the relative current-carrying capacity is quadrupled.

The provision of three-phase supplies would involve an increased cost not only for the low-voltage distribution main, but also for the high-voltage spur line and transformer.

Electric supply to isolated country houses and farms almost without exception should be given by a single-phase 11,000/230-volt two-wire tapping of the high-voltage main. In houses a motor load is unusual, and the domestic requirements can be supplied by single phase with less likelihood of voltage fluctuation than if such load were split over a three-phase service. Properly balancing three phases is particularly difficult where cookers, which normally must be connected to only one phase, are used. This usually requires a larger transformer than would be necessary with the single-phase system, which allows some diversity advantages.

Precisely the same arguments apply to all farm load, with the exception of motors, which will be required eventually. Much misapprehension exists in relation to the motor load, and it is feared that without proper consideration three-phase supplies frequently are provided to farms with much unnecessary capital cost. The power requirements of most farms can be supplied readily by a motor of some five to seven and one-half horsepower, and there are relatively few farms requiring motors exceeding ten horsepower in size. Single-phase motors now are available with much improved starting characteristics, and the slight extra cost incurred by the customer is fractional compared with the aggregate saving to the supply authority in capital cost of mains and services. This saving is reflected back to the customer by a reduction or complete elimination of the service connection charge.

Rate Determinations Are Important in England

In Great Britain electrical operations are more generally under the management of electrical engineers than are electrical properties in the United States, where public utility properties in many instances are under the management of bankers and lawyers. Having in mind that in any rural area the domestic load from small premises will predominate in both consumption and revenue, correct practice in the use of slot meters is of the utmost importance. Indeed the correct use of slot meters is believed to be the key to increased revenue and a vital factor in the success of rural plans.

The principal types suitable for the development of general domestic loads fall into the following groups: (*a*) stepped-rate, (*b*) double-circuit, (*c*) change-price, (*d*) two-part. Results regarded with satisfaction have been obtained with each of the types. Much satisfactory development has been achieved even by the use of a flat-rate meter giving domestic supplies at an equated rate of one penny per unit or less. That method, and each of the types (*a*), (*b*), (*c*), have limitations which either do not permit their use by each and every domestic customer, or do not encourage the maximum domestic use obtainable by a straightforward two-part tariff. The two-part tariff meter, arranged so as to collect a fixed and a running

charge ["fixed charge" and "running charge" in British nomenclature correspond in a general way to the American "demand" and "energy" charges, respectively] appears to be the only one enabling the supplier to offer the slot-meter consumers precisely the same terms as are usually available to those consumers who choose to pay their accounts quarterly, and this consideration appears to place this type first in order of preference. With this type, any two-part tariff containing a fixed annual or quarterly charge can be resolved to a weekly basis, and the slot consumer thereby is offered precisely the same terms as the quarterly consumers.

Maximum Demands

Estimates of the maximum demand likely to result from service to a given number of consumers are always a source of speculation. Large errors can be made, usually in overestimating the demand, unless adequate allowance is made for diversity. The diversity of use even in a single household is surprising, and if allowance is made for the additional diversity between separate consumers, and also between different parts of a large supply area, the result is remarkable. In a city or urban area where fixed times for the commencement and cessation of business affect the majority of consumers there is not the same diversity as in a rural area where habits may vary greatly between different parts and therefore the diversity can be very large.

Table II. Total Connected Load, Resulting System Maximum Demand, and Various Derived Figures

	Year of Trading				
	Preliminary	First	Second	Third	Fourth
Connected Load (Kilowatts)					
Lighting	333	1,319	2,068	2,523	2,700
Heating	236	1,027	3,384	4,800	5,638
Motive power	114	819	1,424	2,117	2,519
Cooking	650	2,325	4,100	9,505	12,630
Total	1,333	5,490	10,976	18,945	23,487
System Maximum Demand (Kilowatts)					
Total	150	780	1,409	2,445	2,571
Per consumer	0.20	0.30	0.30	0.39	0.34
Per head of population	0.003	0.013	0.024	0.042	0.044
Diversity					
Ratio of connected load to system maximum demand		7.0	7.8	7.8	9.1

The figures of connected load and resulting system maximum demand shown in table II relate to a large rural area of approximately 1,000 square miles. Obviously there has been some difficulty in obtaining accurate records of the connected loads for those items of domestic equipment, notably heating units, which consumers purchase and use without notification, and a little estimating has been necessary in computing that item. All other items are known to be fairly accurate, especially the predominating figures relating to cookers. The system maximum demand tends toward a figure of about one-tenth of the total connected load.

The Dumfries County System

During the last five years a complete electric distribution system has been put into operation in Dumfriesshire by the county council of that area. This system is of special interest because the supply area, which covers an entire geographical county with the exception of one town, is a self-contained area in which no electric service had been available previously. The policy toward consumers, which aims at providing service to all consumers within the area on equal terms, is notable in that supply has been given to every consumer without any contribution toward capital cost, irrespective of the length of the necessary service main, and without the payment of any guaranteed minimum revenue.

The supply area is 1,070 square miles in extent and has a population (1931 census) of only 58,252. The area is almost entirely agricultural in character, with a little associated industry in a few creameries, sawmills, quarries, and grain mills. The total number of occupied dwelling houses within the area is 14,176, and the total possible number of consumers may be taken at the round figure of 15,000.

The tariffs, which have remained practically unchanged since the beginning, are shown in table III. The flat rates are kept comparatively high to encourage the free adoption of two-part tariffs. Two-part-tariff prepayment meters are provided without extra charge.

Table III. Schedule of Tariffs

Premises	Fixed Quarterly Charge	Running Charge (Pence per Unit)
Dwelling houses	5s. per room (maximum 20 rooms) boxrooms, bathrooms, sculleries, attics, and cellars not chargeable	3/4
Farms	7s. 6d. per room. All use, including motive power, allowed at normal running charge (3/4d. per unit)	3/4
Trade or business premises	5s. per 100 square feet for first 1,000 square feet 2s. 6d. per 100 square feet for all additional	3/4
Other premises	One-half of charges under previous item	3/4
Street lighting	7s. per lamp. Street-lighting authority to provide equipment	3/4
Alternative flat rates	Lighting 8d. per unit, heating 1 1/2d. per unit	—
Motive power	Block rate, sliding from 2 1/2d. to 3/4d.	—

Transmission and Distribution System

Bulk supply is obtained from the Central Electricity Board. The high-voltage network, which is almost exclusively overhead, consists of one 33-kv feeder 20 miles long, a general 11-kv three-phase system totaling 304 route miles, and several single-phase 11-kv spur lines totaling 191 miles. The aggregate length of low-voltage lines is 163 miles. All isolated consumers such as in

country houses, farms, and small groups of houses, are supplied by single-phase tappings of the 11-kv network. Low-voltage distribution is done on the three-phase system in burghs and large villages, and by the single-phase three-wire system in small villages, at the standard voltage of 230.

Working Results

Part of the year 1931 and the entire year of 1932 were occupied in constructional work on the Dumfriesshire system. First supplies under the principal plan were made available in February 1933. The period prior to 1933 has been regarded as preliminary, and the first full year of trading was the year ending May 15, 1934. The undertaking is now in its fifth year, and the actual working results given hereafter are for the first four years, with estimated figures for the fifth year. By the end of the fourth year 7,508 consumers, or 50 per cent of the total possible number of consumers in the whole area, had been connected to the supply. It is estimated that by the end of the fifth year the number of consumers will have increased to 8,500, or 57 per cent. Moreover, distribution mains have been provided from which a large number of other consumers may be connected at little more than the cost of services. It is estimated that already a supply is available from existing low-voltage mains to not less than 11,000 premises, representing 73 per cent of the total possible consumers in the whole area. Domestic use accounts for 83 per cent of the total energy sales, while power consumers, who are few in number and whose load is small, account for only 17 per cent. By comparison, in all of England the total sales by authorized electric services are made up of 35 per cent for domestic purposes and 65 per cent for power and traction. The use of cookers in rural areas has proved to be particularly popular, and the two-part tariff has been adopted by 66 per cent of the consumers.

At the end of the fourth year, 678 miles of mains and 741 pole-type transformers had been provided to supply 7,508 consumers. This is roughly equivalent to one mile of distribution main and one transformer for every ten consumers, a striking indication of the scattered nature of the population. From published records it appears that over the whole country the average figure is 62 consumers per mile of main. The proportion of high-voltage mains, namely 515 miles in a total of 678 miles, shows that the distribution is largely carried out at 11,000 volts. Among the entire 7,508 consumers 2,526 cookers were in use, or by about one consumer out of every three. Eliminating the business premises, it appears probable that a proportion of one cooker to every two domestic consumers soon will be reached. Although the number of consumers has increased rapidly from year to year, the domestic energy use per consumer also has increased rapidly from 530 units in the first year to 960 units in the fifth year.

Conclusions

The author believes that a budgetary policy, in which deficiencies or narrow margins of profit in the early years of a venture in rural electrification are balanced against the increasing returns of later years, can be adopted safely, since the ultimate financial success of rural electrification is reasonably assured. A ten-year basis is suggested; and although rural schemes cannot be expected to provide for both interest and depreciation from their inception, in general a self-supporting basis will be reached by the end of five years.

Minimum capital cost of construction and rapid expansion of revenue are essential for the success of rural electrification. Underground cables never should be used except in circumstances prohibiting the use of overhead lines or surface wiring.

To promote the development of revenue, adequate apparatus-rental and assisted-wiring plans are essential. Rental plans always should include free repair and maintenance of apparatus. Assisted-wiring schemes can be undertaken confidently on a large scale, since, unlike rental plans they involve neither obsolescence nor material maintenance during the period of purchase. In all such plans the use of simple agreements not burdened by restrictive clauses, and the elimination of deterrents such as initial payments, have a strong stimulating effect on development.

Special prominence should be given to the two-part methods of charge in all printed tariffs and publicity matter and in all correspondence and canvassing. The flat rates should be regarded as alternatives, and be kept relatively high so as further to encourage the adoption of the two-part tariffs, the primary charge of which should be kept fairly high so as to permit the secondary rate being relatively low.

Wherever possible, service connections should be made free. A service charge, however trivial, is a perpetual source of annoyance to prospective customers, and may have a retarding effect on development. A method of guaranteed revenue is preferable to that of capital contributions, since the consumer usually will arrange to make corresponding use of the supply; nevertheless, development of a rural area should be possible without requiring any capital contribution or guaranteed revenue.

The average revenue obtainable from domestic consumers in rural areas is higher than the corresponding revenue obtainable in city and urban areas, and, in consequence, electrification in rural areas may be expected ultimately to be as remunerative as that in urban areas.

News

Of Institute and Related Activities

54th Annual Summer Convention First To Be Held in Washington, D. C.

THE annual summer convention held June 20–24 at the Mayflower Hotel in Washington, D. C., 54th such meeting to be held by the Institute, was the first to be held in the nation's capital city. For what is now District 2, this was the eighth summer convention, others having been held as follows: Philadelphia, Pa., 1884, 1894, 1900; Deer Park, Md., 1915; Cleveland, Ohio, 1916, 1932; White Sulphur Springs, W. Va., 1926.

Attendance figures are given in an accompanying tabulation, and highlights of the convention are reported on this and the following pages.

Annual Business Meeting

Departing from the practice of recent years, the Institute's official annual meeting was held the morning of the second day of the convention rather than the first. This meeting was opened promptly at 9:30 Tuesday morning June 21 in the main ballroom of the Mayflower Hotel by Chairman H. W. Osgood of the general convention committee. A cordial welcome to Washington and an explanation of the various attractive features provided by the convention committee was given by Doctor William McClellan, past president of the Institute (1921–22) and honorary chairman of the general convention committee. For the conduct of the business meeting, President W. H. Harrison took the chair and paid tribute to the summer convention committee for the results of its work.

Reports of the Board of Directors and the Committee of Tellers

National Secretary H. H. Henline presented a digest of the annual report of the board of directors for the fiscal year ending April 30, 1938, pointing out that the full text of the report would be published and thus available for every member of the Institute (*EE July '38 pages 305–15* inclusive). This report contains information that should be of interest to every active member of the Institute. Among the highlights reflected by Mr. Henline were the following: that the three national conventions and two District meetings held during the year had attracted larger numbers than usual and showed an increase in interest in what the Institute and its various divisions are doing; that three new Sections had been formed, bringing the total number to 65, and that the year's total number of Section meetings was the largest ever reported; that one new Student Branch formed during the year brought the total number of these units up to 120; and that the enrollment had reached a total at the end of the year of about 500 higher than last year; and that 1,671 applications for membership received during the year had resulted in a net membership increase of 770, bringing the total up to 16,078 at the end of the fiscal year.

Details concerning Section and Branch activities for the year 1937–38 may be found in the comprehensive annual report published in the recent June issue of Electrical Engineering beginning on page 263. Other items concerning Section and Branch activities have been published throughout the year.

Reports of the committee of tellers covering both the election of officers and the amendments to the constitution were published in the recent July issue of Electrical Engineering on page 303.

Treasurer's Report

National Treasurer W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y., verified the condition of Institute accounts as covered in the auditor's statement published as a part of the report of the board of directors. In surveying the Institute's general fiscal position, Treasurer Slichter reported that for the third successive year a favorable balance had enabled the placement of nominal amounts in the reserve capital account, thus providing against future possible unfavorable balances. He reported that reserves consist mostly of bonds, with some stocks, which on May 21 showed a ratio of market value to book value of 87 1/2 per cent, a very favorable record.

Prize Awards

Prize awards for technical papers presented during 1937 were announced on behalf of the AIEE committee on award of Institute prizes by Dean J. W. Barker of Columbia University, New York, N. Y., in the absence of Chairman H. S. Osborne. This report was published in full beginning on page 262 of the recent June issue of Electrical Engineering. The initial paper prize for District 2 for 1937 was announced by Vice-President I. Melville Stein as having been awarded to F. I. Morgan of the Pennsylvania Water and Power Company for a paper "An Electric Governor" presented before the Baltimore Section.

At the conclusion of the business session, an address "Municipal Planning in Washington" was delivered by Colonel Dan I. Sultan, engineer commissioner for the District of Columbia, who described the history and development of the capital city.

Lamme Medal for 1937 Presented to Doctor R. E. Doherty

To Doctor R. E. Doherty (A'16, M'27) president of Carnegie Institute of Technology, Pittsburgh, Pa., the tenth AIEE Lamme Gold Medal was presented during the summer convention business session "for his extension of the theory of alternating current machinery, his skill in introducing that theory into practice, and his encouragement of young men to aspire to excellence in this field." President Harrison made the presentation following a discussion of the award and its donor by Chairman N. E. Funk of the Lamme Medal committee, and an outline of the professional attainments and career of the recipient given by A. R. Stevenson, Jr. (A'20, F'37) of Schenectady, N. Y., a former associate of Doctor Doherty's. A biographical sketch of Doctor Doherty was published in the recent March issue of Electrical Engineering, page 141, and Mr. Stevenson's dissertation is scheduled for inclusion in an early issue.

Established for the encouragement and recognition of "meritorious achievement in the development of electrical apparatus or machinery," the AIEE Lamme Medal is one of three bequests provided in 1924 in the will of Benjamin Garver Lamme.

Other Bequests

One of the other bequests was made to Ohio State University, Columbus, which

Table I. Analysis of Attendance at 1938 Summer Convention, Washington, D. C.

Classification	Dist. 1	Dist. 2	Dist. 3	Dist. 4	Dist. 5	Dist. 6	Dist. 7	Dist. 8	Dist. 9	Dist. 10	Foreign	Totals
Members	71	297	94	35	50	7	20	5	7	7	3	596
Enrolled Students	2	11		1	1							15
Men guests	10	43	10		6		2			2	11	84
Women guests	15	61	16	9	11		9	1	3	3	2	130
Totals	98	412	120	45	68	7	31	6	10	12	16	825

Table II. Summer Convention Attendance During Recent Years

1938	Washington, D. C.	*(2)	825
1937	Milwaukee, Wis.	(5)	1,067
1936	Pasadena, Calif.	(8)	715
1935	Ithaca, N. Y.	(1)	904
1934	Hot Springs, Va.	(4)	351
1933	Chicago, Ill.	(5)	968
1932	Cleveland, Ohio	(2)	1,022
1931	Asheville, N. C.	(4)	525
1930	Toronto, Ont., Canada	(10)	1,110
1929	Swampscott, Mass.	(1)	1,000

* District numbers in parentheses.

recently awarded its current medal "for meritorious achievement in engineering" to Professor Emeritus James E. Boyd, for 28 years chairman of the department of mechanics. The remaining bequest was made to the Society for the Promotion of Engineering Education, which recently announced its current (eleventh) award to R. L. Sackett, dean of the college of engineering at Pennsylvania State College from 1915 to 1937.

Planté Medal to Doctor Vinal

A colorful highlight of the convention was the presentation to Doctor G. W. Vinal, of the Gaston Planté Medal and 4,500-franc prize, previously announced in ELECTRICAL ENGINEERING (Feb. '38, page 85). On behalf of the Société Française des Electriciens, his excellency Count de Saint-Quentin, Ambassador of the French Republic, made the actual presentation before the 290-odd guests assembled for the formal convention banquet held Thursday evening June 23. For the benefit of those assembled, Doctor E. Crittenden (A'19, M'22) assistant director of the U. S. National Bureau of Standards briefly sketched the scope and significance of the work that has been done by Doctor Vinal in the field of international standards and especially in the development of the electric storage battery.

Principal physicist of the U.S. Bureau of Standards since 1929, and chief of the Bureau's section of electrochemistry since 1918, Doctor Vinal has devoted himself principally to electric batteries, including standard cells, dry cells, and storage batteries. Special credit is given to him for improvement in both dry cells and storage batteries to meet rigorous military requirements growing out of the world war. Also, he took an important part in the extensive researches conducted from 1908 to 1917 which established the reliability of the silver voltameter as the primary standard for measurement of electric current in the "International" system of units. He served as the representative of the United States in the co-operative measurements made with the voltameter in Berlin in 1931, and prepared the report on the silver voltameter for the International Electrical Congress in Paris in 1932.

The Gaston Planté medal was established June 10, 1935 by the Société Française des Electriciens "to honor the memory of the illustrious philosopher who added to the progress of an industry born of his invention." "To any person, French or foreigner, who, by his works of a scientific or technical nature, will bring an important contribution to the industry of electric accumulators, electric piles, or electrochemistry in general," the silver-gilt medal is intended to be awarded every three years accompanied by a prize of about 4,000 francs. The commission of award is made up of officers of the Société and officers and members of the committee of celebration of the centenary of Gaston Planté. Regulations provide that electrotechnical societies of each country may propose a candidate for the choice of the commission. For the initial award of the Planté medal the American Institute of Electrical Engineers successfully proposed the name of its distinguished member, Doctor George W. Vinal.

C. C. Chesney Elected to Honorary Membership

As announced in the current July issue of ELECTRICAL ENGINEERING, Past President Cummings C. Chesney (A'94, M'99, F'13) was elected this spring to honorary membership in the Institute. Formal announcement of this fact was made during the business session of the recent summer convention by President W. H. Harrison who presented a certificate to Mr. Chesney. In 1921 Mr. Chesney received the Institute's Edison Medal "for early developments in alternating-current transmission." Active in the electrical industry for 50 years and in Institute affairs for 44 years, Mr. Chesney becomes the tenth living Honorary Member, and the 34th person so to be honored by the Institute in its 54 years of existence. The other living Honorary Members are: B. J. Arnold ('37); A. E. Blondel ('12); Alex Dow ('37); W. L. Emmet ('33); Herbert Hoover ('29); A. E. Kennelly ('33); R. A. Millikan ('33); C. F. Scott ('29); M. Shibusawa ('29).

The grade of Honorary Member is the highest in the AIEE, and is provided for in Sections 8 and 9 of the Institute's Constitution, which stipulate that "Honorary Members may be chosen from among those who have rendered acknowledged eminent service to electrical engineering or its allied sciences." Proposal by at least 10 members and subsequent to unanimous affirmative action of the board of directors is required for election. The board elected Mr. Chesney at its May 26 meeting.

Other Convention Features

Technical and general sessions and entertainment features were run off essentially in conformity with the schedules as published in the news section of the June issue of ELECTRICAL ENGINEERING. The 48 technical papers accommodated by the 10 technical sessions ultimately will be published in ELECTRICAL ENGINEERING or TRANSACTIONS. Brief reports covering the six technical conferences and of certain technical committee sessions may be found elsewhere in this issue. Of the several special addresses presented, the president's annual message was published in the July issue beginning on page 279, and the address by Dr. Gregg on weather forecasting is scheduled for inclusion in an early issue.

The convention meeting of the board of directors is reported elsewhere in this issue. Following the board meeting Thursday afternoon, June 23, a special conference was attended by vice-presidents, District secretaries, and counselor-delegates. Institute operating problems were discussed, but no actions were taken.

SPORTS EVENTS

National competition among Institute members on the basis of match play and handicap for the Mershon trophy was won by T. O. Rudd (A'26) of New York, N. Y., with J. H. Irwin (A'20) Washington, D. C. as runner-up; handicap in each case, five. Mr. Rudd thus becomes the third to have his name engraved upon the present trophy, which is the third cup donated by Past President Ralph Mershon. This trophy remains on display at Institute headquarters.

The Lee trophy, presented in 1932 by the late Past President W. S. Lee is awarded each year to the player having the lowest net score for 36 holes, and must be won

Summer Convention

At the head table from left to right: National Secretary H. H. Henline, Past President P. M. Lincoln; C. A. Robinson, vice-chairman, general convention committee; Doctor E. C. Crittenden, assistant director, National Bureau of Standards; Doctor G. W. Vinal, Gaston Plante Medalist; His Excellency, Count de Saint-Quentin, ambassa-

twice by the same player for permanent possession. As the result of the 36-hole medal play in Washington, T. A. O'Halloran (A'36) of Washington, D. C. with a net score of 138 became the seventh person to win a leg on the cup and the privilege of having his name engraved thereon; runner-up was F. W. Altrup (A'32) of Washington, D. C.; handicaps respectively 24 and 19. In the initial rounds, J. H. Irwin and F. W. Altrup were tied for second place with a score of 147.

By virtue of winning the men's tennis singles, C. B. Oler (M'35) became the fourth to have his name engraved upon the present Mershon trophy which was donated in 1935 by Past President Mershon; runner-up was J. d'Harcourt (A'22) of Paris, France. Men's doubles were won by A. O. White (A'22, M'34) and L. W. Bates (A'04) of Washington, D. C., with S. B. Crary (A'31, M'37) of Schenectady, N. Y., and R. B. Hubbard (A'20, M'28) of Denver, Col., as runners-up. Mixed tennis doubles were won by Mr. and Mrs. A. O. White, with Mr. and Mrs. D. C. Prince of Philadelphia, Pa., as runners-up. Women's singles competition was won by Mrs. A. O. White, with Mme. J. d'Harcourt of Paris, France, as runner-up.

In the table tennis competition, the winner among the women was Mrs. F. B. Crider of Washington, D. C.; winner of the men's competition was Professor W. L. Everitt (A'25, F'36) of Columbus, O. Women's putting contest was won by Mrs. C. A. Corney, Boston, Mass., with second and third places going respectively to Mrs. R. K. Lane, Tulsa, Okla., and Mrs. C. Birdwell, Louisville, Ky.

All sports competitions were held at the Congressional Country Club. Officially starting in the various tournaments were: 24 players in the Lee and Mershon golf event; 16 women in the putting contest; 8 men and 4 women in the tennis singles; 4 teams in the mens tennis doubles, and 4 teams in mixed doubles. A choice variety of valuable prizes was distributed by the local committee.

Future AIEE Meetings

Pacific Coast Convention
Portland, Ore., August 9–12, 1938

Southern District Meeting
Miami, Fla., November 28–30, 1938

Winter Convention
New York, N. Y., January 23–27, 1939

South West District Meeting
Houston, Texas, Spring, 1939

North Eastern District Meeting
Springfield, Mass., May 1939

Summer and Pacific Coast Convention (combined)
San Francisco, Calif., June 26–30, 1939

Middle Eastern District Meeting
Scranton, Pa., October 11–13, 1939

Great Lakes District Meeting
Minneapolis, Minn., Fall, 1939

Annual Conference of Officers, Delegates, and Members Held at Washington, D. C.

UNDER joint sponsorship of the AIEE committees on Sections and Student Branches, the annual conference of officers, delegates, and members was held Monday, June 20, 1938 at Washington, D. C., on the first day of the summer convention. Sessions were held in both morning and afternoon, and were attended by delegates from 58 of the Institute's 65 Sections, 6 of the 10 District secretaries, counselor delegates from 8 of the 9 Districts in which committees on student activities had been organized, and many other local and national officers of the Institute and members interested in Institute activities. W. H. Timbie, chairman of the Sections committee, presided. Topics discussed were as follows:

10:00 a.m.

1. Opening remarks, including comments on Section representation on national committees—Chairman W. H. Timbie.

2. Ways and means of encouraging the preparation and submission of papers suitable for prize awards—I. Melville Stein.

3. National membership reinstatement and transfer policies—Harold Goodwin, Jr.

4. Contacts with preparatory-school guidance teachers and prospective engineering students—M. S. Coover.

5. Miscellaneous Section problems.

2:00 p.m.

6. How can Sections contribute to and become acquainted with the work of the A.E.C.—William McClellan.

7. Symposium on registration of engineers.
(*a*) History and philosophy of licensing—L. W. W. Morrow.
(*b*) Model law—C. R. Beardsley.
(*c*) General discussion.

8. Miscellaneous Section problems.

Following the discussion of items 1 and 2 in the morning session, the conference was divided into two parts, the Sections delegates and Student Branch counselors holding separate sessions. Under "Miscellaneous Section problems," the following topics were discussed: term of office of Section officers; revised TRANSACTIONS format; technical sessions for Section meetings; publication policy with respect to Section papers; and Section co-operation.

Opportunity was provided for general discussion from the floor on all subjects. These discussions constituted an interchange of ideas among the Section delegates and other interested officers and members that proved mutually helpful. At the conclusion of the afternoon session, Chairman Timbie introduced President-Elect John C. Parker who spoke briefly.

PHILOSOPHY OF REGISTRATION DISCUSSED BY L. W. W. MORROW

Thirty-nine states now have laws requiring the registration and licensing of engineers, and other states have active committees advocating the passage of such laws, according to L. W. W. Morrow (A'13, F'25) who addressed the conference on the history and philosophy of registration. Some 47,000 engineers have been licensed under these laws. Mr. Morrow first traced the licensing movement from its early beginning in the West to its present status.

"The philosophy of the licensing movement as such" he said, "is to give a professional and legal status whereby the profession itself, in return for service rendered, can

Formal Dinner

dor of the French Republic; Doctor W. H. Harrison, president AIEE; Doctor William McClellan, past president AIEE; Doctor J. C. Parker, president-elect AIEE; Past President H. P. Charlesworth; Past President A. M. MacCutcheon; General Convention Chairman H. W. Osgood, whose committee did a thorough job

Photo by Rideout

Membership—

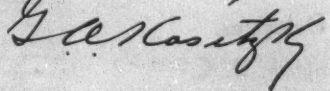
Members of the Institute:

The past two years of my AIEE activities have been made most pleasant by the many close associations with you as chairman of your membership committee.

The committee is pleased to report an increase in Institute membership, during these two years, from 14,600 to 16,078, or about ten per cent of the 1936 total.

This is a committee that deserves and has received unified help from the whole membership. Though individually you may not realize it, collectively your own boosting has been the major force accounting for our steady growth. The field is still fertile and I hope you will continue your good efforts after the new chairman takes over this month.

With sincere thanks and appreciation to you and with best wishes to my successor and his committee, I sign finally as,



Chairman,
National Membership Committee

fix its standards, can fix its qualifications, can fix its rules of conduct. . . . . it offers to us an opportunity for advancement we have not had heretofore. I think if we neglect participation in this movement, it is going to get into unwise hands. I think if we neglect it, we are going to see our young engineers graduating from college today drift off into a unionization movement that has hazards. . . . .My plea is that you can establish the profession in a practical manner through this licensing and registration movement if the engineers themselves get back of it.

Status of Model Law
Reported by C. R. Beardsley

Speaking as chairman of a special committee to draft a model law, C. R. Beardsley (A'08, F'30) briefly reviewed the position of the AIEE with respect to licensing legislation stating that: "There are continually coming before the legislatures amendments and modifications of the laws, and these in general are tending toward a much greater restriction, a much more rigid requirement. They go beyond the minimum requirement which should be made in order that all engineers be licensed."

After briefly reviewing the various efforts to establish a model law that have been made from time to time by various groups, Mr. Beardsley quoted the following items from the code of principles that had been prepared as a basis for drafting the AIEE model law:

1. Legislation of this type is enactable only for the public benefit and should be limited to that objective. Any benefit to the profession should be incidental.

2. Legislation is prefaced with statement of purpose. The purpose of enactments on licensing engineers usually reads "in order to safeguard life, health, and property." Enactments should avoid embodying provisions beyond the stated purposes and for unnamed ulterior objectives because such provisions would depart from the basic principle of truth which is the keystone of ethical engineering practice.

3. Public benefit will be protected in the maximum possible degree if it is assured that those who offer engineering services to the public are competent to render the service contemplated. Legislation can assure that certain minimum standards of competence exist and can provide for enforcement. It cannot attempt more than this. The public must determine for itself any necessity for competence in excess of the minima. Higher development of engineering competence beyond these minimum requirements continues to be the objective of engineering educational institutions and engineering societies, and its attainment is assured without legal requirement.

4. To assure these conditions it is not necessary that all engineers be subject to legislation, but only those who offer service for hire, or are public employees.

"We have taken the position," he continued, "that we should not attempt to work into a law a benefit to the profession which is not stated in objectives of the law. I don't think we will get very far with the legislatures in the enactment of new laws if we say we want this law so written that the engineering profession will have its rates of compensation raised, or be put in a better position."

Mr. Beardsley reported that the proposed model law that has been drawn up by the committee, based upon these principles, is now undergoing legal scrutiny.

Following the addresses by Messrs. Morrow and Beardsley, the whole subject of registration was discussed at some length. Several delegates reported that their Sections had been active in preventing the passage of improper licensing legislation and also in assisting in drafting or revising state registration laws. Mr. Beardsley asked that the committee be given the benefit of any additional comments or suggestions that members may wish to offer.

Term of Section Officers

Among the several Sections problems discussed at the conference, was a proposal to change the date on which Section officers assume their duties. Many delegates reported that their Sections had found it advantageous to begin their administrative years on dates other than January 1 or August 1, as specified in the AIEE by-laws. Either June 1 or July 1 appeared to be preferred by several Sections.

The subject was discussed at some length, but a motion to pass a resolution that the by-law be changed was tabled. Subsequently, however, Chairman Timbie of the Sections committee appointed a special subcommittee to consider the matter. As a result, the Sections committee submitted the following recommendation to the board of directors at its June 23 meeting:

1. That the dates for the beginning of Section administrative years be deleted from section 43 of the by-laws so that each Section may begin its administrative year at the time which is best suited to local conditions.

2. That section 43 of the by-laws be modified by deleting the second sentence, after which this section of the by-laws would read as follows:

"The chairman and secretary of each Section shall be elected for the term of one year, beginning upon the date specified in the by-laws of the Section. The by-laws of the Section shall determine whether or not these officers shall be eligible for re-election."

The board approved the recommendation and voted that the prescribed procedure be followed for the revision of section 43 of the by-laws as recommended (see report of board of directors meeting elsewhere in this issue).

Section Papers and Discussions

Another Section problem discussed at the conference related to the publication policy with respect to Section papers and discussions. Section 45 of the AIEE by-laws covering this point reads:

Papers and discussions presented before a Section or Branch shall be the property of the Institute, and may be published only on authorization of the Publication Committee. Where publication in Transactions of Section or Branch papers by non-members of the Institute is involved, approvals shall be obtained in accordance with Section 95 of the By-Laws.

Several delegates reported that a literal interpretation and enforcement of this by-law would seriously hamper them in their effort to obtain speakers at Section meetings because some speakers prefer to retain publication control of their material. Chairman I. Melville Stein of the publication committee called attention to the fact that the by-law under discussion was one of long standing, that its interpretation in recent years had been liberal rather than strict. He mentioned also the membership demand for the publication of Section papers in

ELECTRICAL ENGINEERING and the efforts of the publication committee to supply that demand. However, he drew a distinction between a Section "paper" and "talk." "Where speakers speak from cards or from no notes at all," he said, "there is no paper; it is just a talk, and the by-laws don't apply." Where Section meeting speakers do prepare manuscripts he said that arrangements sometimes are made for simultaneous publication in ELECTRICAL ENGINEERING and another publication.

As the outcome of the discussion on this subject, a motion was passed authorizing the appointment of a committee to investigate the matter. Subsequently the following were appointed: I. Melville Stein, chairman of the publication committee; A. F. Dixon, chairman of the New York Section; R. G. Lorraine, secretary of the Northeastern District.

STUDENT GUIDANCE DISCUSSED

Professor M. S. Coover (A'16, M'32) reported the results of a canvass of AIEE Sections to determine how extensively the pamphlet "Engineering—a Career, a Culture" had been used in promoting student guidance. On the basis of replies from 30 Sections, the average number of booklets distributed per Section appeared to be between 100 and 150 copies; one Section had distributed none while the maximum distributed by any one Section was 700 copies. Some Sections, particularly those in which the membership is concentrated in a rather small geographic area, had made rather effective follow-ups on the distribution of these booklets. In response to the question "Do you consider that the time and expense in preparing the booklet has been justified?" the answer without exception was "yes."

In the general discussion following Professor Coover's remarks, it was pointed out that many vocational-guidance teachers are not sufficiently familiar with engineering to present the subject effectively to the

Table I. Record of Attendance of Section Delegates and Student Branch Counselors at Washington Conference

Section	Delegate Name and Affiliation
Akron	A. O. Austin (A'04, F'25) manufacturing engineer, Barberton, Ohio; Section chairman 1937–38
Alabama	F. R. Maxwell (M'30) professor of electrical engineering, University of Alabama; Section secretary 1937–38
Baltimore	J. H. Lampe (A'20, M'26) associate professor of electrical engineering, Johns Hopkins University; Student Branch Counselor
Boston	J. G. Patterson (A'14, M'21) engineer of transmission and protection, New England Telephone and Telegraph Company; Section chairman 1938–39
Central Indiana	L. E. Beck (A'29, M'37) assistant professor of electrical engineering, Purdue University
Chicago	J. A. Fitts (A'20) Chicago Branch engineer, Electric Storage Battery Company; Section chairman 1938–39
Cincinnati	J. A. Noertker (A'23, M'32) electrical engineer, Cincinnati Street Railway Company; Section chairman 1938–39
Cleveland	W. C. Kalb (A'12, M'15) Carbon Sales Division, National Carbon Company Incorporated; Section chairman 1938–39
Columbus	C. D. Price (A'23, M'30) substation engineer, Columbus and Southern Ohio Electric Company; Section chairman 1937–38
Connecticut	J. A. French (M'22) assistant engineer, Connecticut Light and Power Company; Section chairman 1937–38
Dallas	E. B. Robertson (M'24) sales engineer; Section chairman 1938–39
Denver	N. R. Love (A'25, M'38) chief engineer, Denver Tramway Corporation; Section chairman 1937–38
Detroit-Ann Arbor	D. H. Baker (A'30) transmission and protection engineer, Michigan Bell Telephone Company; Section chairman 1937–38
East-Tennessee	E. E. George (A'20, F'36) superintendent of system operation, Tennessee Electric Power Company; Section chairman 1937–38
Erie	L. S. Cooper (A'29) transmission engineering department, General Electric Company; Section chairman 1937–38
Florida	A. P. Michaels (A'27, M'37) consulting engineer, A. P. Michaels Engineering Firm; Section chairman 1937–38
Fort Wayne	S. Allen (A'31, M'37) design engineer, General Electric Company; Section chairman 1937–38
Georgia	J. O'D. Shepherd (A'34) cost studies engineer, Southern Bell Telephone and Telegraph Company, Atlanta
Houston	Seth Evans (M'29) electrical engineer, Hughes Tool Company; Section chairman 1938–39
Iowa	O. A. Brown (A'30) assistant professor of electrical engineering, Iowa State College; Section chairman 1937–38
Ithaca	L. A. Burckmyer, Jr. (A'33) assistant professor of electrical engineering, Cornell University; Section chairman 1937–38
Kansas City	M. M. Boggess (A'23) sales agent, General Electric Company; Section chairman 1937–38
Lehigh Valley	E. F. Weaver (A'26) superintendent, Pennsylvania Power and Light Company; Section chairman 1938–39
Los Angeles	W. F. Grimes (A'19, M'27) manager, Radio Interference Engineering Bureau; Section chairman 1937–38
Louisville	F. W. Russell (A'26) electrical construction engineer, Louisville Gas and Electric Company; Section chairman 1937–38
Lynn	E. H. Raddin (A'36) chief engineer, Champion Lamp Works; Section chairman 1938–39
Madison	E. D. Ayres (A'26, M'31) associate professor of engineering economics, University of Wisconsin; Section chairman 1937–38
Memphis	J. H. Tole (A'30) sales engineer, Westinghouse Electric & Manufacturing Company; Section chairman 1937–38
Milwaukee	L. H. Hill (A'22, F'38) engineer in charge, transformer division, Allis-Chalmers Manufacturing Company; Section chairman 1937–38
Minnesota	C. H. Nelson (A'21) appraisal engineer, Minnesota Tax Commission; Section vice-chairman 1937–38
Muscle Shoals	B. B. Bessesen (A'17, M'27) electrical engineer, superintendent of power, Tennessee Valley Authority; Section chairman 1937–38
Nebraska	F. W. Norris (A'19, M'26) associate professor of electrical engineering, University of Nebraska; Section chairman 1937–38
New Orleans	L. T. Frantz (M'19) electrical engineer, Sewerage and Water Board of New Orleans; Section chairman 1938–39
New York	A. F. Dixon (A'14, F'26) director of systems development, Bell Telephone Laboratories, Incorporated; Section chairman 1937–38
Niagara-Frontier	E. J. Rahill (A'32) division transmission engineer, New York Telephone Company; Section chairman 1938–39
North Carolina	M. E. Lake (A'23, M'31) power sales engineer, Duke Power Company; Section chairman 1937–38
Oklahoma City	G. I. Page (A'34) operating engineer, Southwestern Light and Power Company; Section chairman 1938–39
Pittsfield	L. Wetherill (A'27, M'37) assistant engineer, high-voltage bushing engineering department, General Electric Company; Section chairman 1938–39
Portland	C. B. Carpenter (A'23, M'34) engineer, Pacific Telephone and Telegraph Company; Section chairman 1938–39
Rochester	B. M. Werly (A'25, M'34) electrical engineer, Eastman Kodak Company; Section chairman 1937–38
St. Louis	L. O. Campbell (A'20, M'29) assistant to engineer, General Electric Company; Section chairman 1938–39
San Antonio	O. W. Sommers (A'30) engineering department, San Antonio Public Service Company; Section chairman 1938–39
San Francisco	F. S. Benson (A'28, M'36) assistant electrical engineer, Pacific Gas and Electric Company; Section chairman 1938–39
Schenectady	C. E. Kilbourne (A'29, M'37) designing engineer, motor-generator engineering department, General Electric Company; Section chairman 1938–39
Seattle	R. E. Kistler (A'17, M'30) transmission and protection engineer, Pacific Telephone and Telegraph Company; Section chairman 1938–39
Sharon	H. S. Smith (A'23, M'30) section engineer, Westinghouse Electric & Manufacturing Company; Section chairman 1937–38
Spokane	H. L. Vincent (A'25) salesman, Westinghouse Electric Supply Company
Springfield	F. R. Longley (A'25) system planning engineer, Western Massachusetts Companies; Section chairman 1937–38
Syracuse	W. H. Lawrence (A'31) assistant power engineer, Central New York Power Corporation; Section chairman 1937–38
Toronto	R. E. Jones (M'26) assistant engineer, Hydroelectric Power Commission of Ontario; Section chairman 1937–38
Tulsa	R. K. Lane (M'37) vice-president in charge of production, Public Service Company of Oklahoma; Section chairman 1937–38
Urbana	C. A. Keener (A'21, M'28) associate professor of electrical engineering, University of Illinois; Section chairman 1937–38
Utah	J. A. McDonald (A'21) superintendent, service shop, General Electric Company; Section chairman 1938–39
Vancouver	F. L. Code (A'27) instructor, Vancouver Technical School
Virginia	W. F. Nimmo (A'30, M'35) general engineering department, Virginia Electric and Power Company; Section chairman 1937–38
Washington	T. R. Tate (M'24, F'35) chief, power resources and requirements division, Federal Power Commission; Section chairman 1938–39
Wichita	R. R. Miner (A'30, M'37) electrical engineer, Kansas Gas and Electric Company; Section chairman 1937–38
Worcester	T. R. Holton (A'26, M'35) electrical engineer in charge of testing, American Steel and Wire Company; Section chairman 1938–39
Chairman, Sections committee	W. H. Timbie (A'10, F'24) professor of electrical engineering, Massachusetts Institute of Technology, Cambridge

Table II. Record of Attendance of District Student Branch Counselor-Delegates

District	Delegate Name and Affiliation
1	E. M. Strong (A'26) associate professor of electrical engineering, Cornell University, Ithaca, N. Y.
2	J. T. Walther (A'19, M'26) professor of electrical engineering, University of Akron, Akron, Ohio
4	E. F. Smith (A'31, M'34) associate professor of electrical engineering, University of Florida, Gainesville, Fla.
5	G. W. Swenson (A'19, F'36) professor and head of electrical engineering dept., Michigan College of Mining & Technology, Houghton, Mich.
6	L. A. Bingham (A'29) assistant professor of electrical engineering, University of Nebraska, Lincoln, Neb.
7	N. F. Rode (A'22, M'32) professor of electrical engineering, A. & M. College of Texas, College Station, Texas
8	H. H. Skilling (A'28, M'34) assistant professor of electrical engineering, Stanford University, Calif.
9	A. L. Taylor (M'28) professor of electrical engineering, University of Utah, Salt Lake City, Utah

Chairman, Committee on Student Branches—F. Ellis Johnson (A'13, F'31) dean of College of Engineering, University of Missouri, Columbia, Mo.

students in high schools and preparatory schools. It was considered important to extend guidance programs not only to the students themselves but also to the vocational-guidance teachers, either through the teachers colleges where those teachers receive their training, or through direct contact with the teachers. The importance of discouraging those students who are not fitted for engineering from taking engineering courses, as well as encouraging properly qualified students, was emphasized.

New Transactions Format Announced

Chairman I. Melville Stein of the AIEE publication committee announced during the conference that beginning with the September issue of Electrical Engineering the Transactions Section will appear in a three-column instead of the present two-column format. He pointed out that the present size of type used in the discussions is smaller than is recommended for easy reading with the length of line used in the two-column format. With the three-column format, the length of line will be reduced by about one-third, which should improve the readability of the discussions considerably; also, the narrower column width will allow a slightly smaller text type to be used for the papers without impairing readability, thus effecting some space economy. Another advantage of the three-column format cited by Mr. Stein is that some of the waste space now appearing around formulas and illustrations and at the ends of papers will be eliminated. He asked that the members look over the new format when it appears in the September issue and forward to the publication committee any comments they may wish to offer.

Relation of AIEE Sections to AEC

Under the title "How Can Sections Contribute to and Become Acquainted With the Work of the American Engineering Council," Past President William McClellan, who currently is president of AEC, presented briefly a picture of what Council is, the situation that led to its organization, and some of its present activities. He pointed out that Council's primary function is to serve as the Washington "embassy" of the engineering profession.

"You can help," Doctor McClellan told the delegates, "first of all by understanding the need in this profession of ours for . . . a united force; secondly how it is organized, what it does, particularly this ambassadorial function here in Washington. . . ." Specifically, he urged the Section secretaries to "get a copy of our News Letter, our bulletin which comes out every month. Pick out . . . those things that may be interesting to you and present them at your meeting; devote a little bit of time at those meetings in discussing those points. Perhaps somebody will want to make a suggestion to us about them. In other words, realize what the American Engineering Council is; make use of the information that is sent out to tell you what it is doing; make that information of practical value by discussing it somewhat, and the most practical form of discussion, of course, is constructive suggestions as to what further we can do."

Counselor-Delegate Session

With Chairman F. Ellis Johnson of the committee on Student Branches presiding, a group of counselor-delegates and others interested in that phase of Institute work adjourned from the general conference session early Monday forenoon, spending the remainder of the day including an evening dinner session in discussing various problems related to Student Branch activity and other topics of mutual interest. Chairman Johnson reported that he had sent

Table III. Record of Attendance of District Secretaries

District	Delegate Name and Affiliation
1	R. G. Lorraine (A'29, M'36) application engineer, central station department, General Electric Company, Schenectady, N. Y.
4	Stanley Warth (A'28, M'36) division transmission engineer, Southern Bell Telephone and Telegraph Company, Louisville, Ky.
5	A. G. Dewars (A'17, M'27) system planning engineer, Northern States Power Co., Minneapolis, Minn.
6	H. F. McPhail (A'19, M'27) assistant chief electrical engineer, U.S. Bureau of Reclamation, Denver, Colo.
7	L. C. Starbird (A'32, M'35) transmission and protection engineer, Southwestern Bell Telephone Company, Dallas, Tex.
8	A. M. Bohnert (A'12, M'26) district sales manager, Ohio Brass Company, San Francisco, Calif.

questionnaires to the chairman and the counselor of each of the 120 Student Branches, and that to date returns had been received from 53 counselors and 34 student chairmen. An informal discussion ensued concerning some of the points raised; full analysis of the returns had not been completed.

Out of the day's discussions, came the following recommendations concerning Institute policy and procedure with respect to Student Branches:

1. That where local memberships are provided, such membership by upper classmen who are not Enrolled Students in the Institute be discouraged.

2. That the committee on Student Branches be requested to recommend to Student Branches where local members are provided, that no such local members be permitted to vote in electing officers or in determining Student Branch policies.

3. That the committee on Student Branches be requested to canvass all District and sub-District groups of Branches to determine the rules and regulations now applying in the conduct of student paper competitions, and report to all Branch counselors.

4. That it be recommended that in the annual report of Branch activities which is published, those institutions requiring attendance at Branch meetings be identified.

AIEE Directors Meet During Summer Convention

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at the Mayflower Hotel, Washington, D. C., on Thursday, June 23, 1938, during the annual summer convention of the Institute.

Present: *President*—W. H. Harrison, New York, N. Y. *Past Presidents*—A. M. MacCutcheon, Cleveland, Ohio; J. B. Whitehead, Baltimore, Md. *Vice-Presidents*—O. B. Blackwell, New York, N. Y.; L. T. Blaisdell, Dallas, Tex.; M. J. McHenry, Toronto, Ont.; I. Melville Stein, Philadelphia, Pa.; A. C. Stevens, Schenectady, N. Y.; Edwin D. Wood, Louisville, Ky. *Directors*—C. R. Beardsley, F. Malcolm Farmer, and C. R. Jones, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear and F. H. Lane, Chicago, Ill.; F. Ellis Johnson, Columbia, Mo.; W. B. Kouwenhoven, Baltimore, Md.; K. B. McEachron, Pittsfield, Mass.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y. By invitation: *Past Presidents*—H. P. Charlesworth and F. B. Jewett, New York, N. Y.; P. M. Lincoln, Ithaca, N. Y.; William McClellan, Washington, D. C. *Officers-Elect*—John C. Parker, New York, N. Y.; Chester L. Dawes, Cambridge, Mass.; and Leland R. Mapes, Chicago, Ill.

Minutes were approved of the meeting of the board of directors held on May 26, 1938.

A report of a meeting of the board of examiners held on June 15, 1938, was presented and approved. Upon recommendation of the board of examiners, the following actions were taken: 6 applicants were transferred to the grade of Fellow; 15 applicants were transferred and 7 were elected to the grade of Member; 80 applicants were elected to the grade of Associate; 53 Students were enrolled.

Expenditures in June, amounting to $20,552.71, were reported by the chairman of the finance committee and approved by the board.

Approval was given to the dates and location, October 11–13, Scranton, Pa., for the previously authorized Middle Eastern District meeting to be held in 1939.

Professor W. J. Miller was appointed a

representative of the Institute on the delegatory committee for Region IV in connection with the program of the Engineers' Council for Professional Development in the accrediting of engineering curricula, which is being conducted by its committee on engineering schools.

Upon request of the Detroit-Ann Arbor Section, and recommendation of the Sections committee, the board authorized a change in name of that Section to "Michigan Section," as the territory of the Section had expanded and a considerable number of its members reside in other communities in the state.

The board approved in principle a recommendation of the Sections committee "that the dates for the beginning of Section administrative years be deleted from Section 43 of the By-laws so that each Section may begin its administrative year at the time which is best suited to local conditions," and directed that the prescribed procedure be followed for revising Section 43 of the By-laws accordingly.

The members of the board were unanimous in an expression of appreciation of the arrangements that had been made for the 1938 summer convention.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Reports of Five Technical Conferences Held During the Summer Convention

AS A MEANS of stimulating a direct, informal interchange of thoughts on subjects of a somewhat specialized nature, five technical conferences were held during the AIEE 1938 summer convention. Brief reports of those conferences are presented here. These reports were prepared by the conference chairman, or from notes furnished by them.

Definitions

By Michel G. Malti, Chairman

The technical conference on definitions, covering several sections of the fundamental definitions (group .05) was attended by over 30 members. The chairman outlined the purpose of the conference by stating that the committee on basic sciences is sponsoring this series of conferences on definitions in an effort to help subcommittee 1 of committee 42 [American Standards Association sectional committee on definitions] in framing better definitions. He also asserted that this work is an integral part of the functions of the committee on basic sciences and in fact of all technical committees.

Written discussions were prepared by the following:

A. Boyajian (A'18, F'26), General Electric Company, Pittsfield, Mass.

M. G. Malti (M'34), Cornell University, Ithaca, N. Y.

K. W. Miller (A'23, M'29), Utilities Research Commission, Chicago, Ill.

S. A. Schelkunoff (M'34), Bell Telephone Laboratories, New York, N. Y.

Ernst Weber (A'31, F'34), Polytechnic Institute of Brooklyn, Brooklyn, N. Y.

Following each written discussion the meeting was open for general discussion. This was extremely lively. The interest displayed was excelled only by the friendliness and harmony which prevailed throughout the conference.

Doctor H. L. Curtis (A'21, F'26), of the National Bureau of Standards, Washington, D. C., chairman of subcommittee 1 of committee 42, laid before the conference a few definitions which, he stated, had caused considerable discussion by his subcommittees. Several members commented on these definitions.

It is my belief that this series of conferences on definitions has been extremely helpful in that:

a. They have stimulated general interest, on the part of the Institute membership as a whole, in an important phase of Institute activity which has heretofore been handled exclusively by committees.

b. They have emphasized the importance of accurate, exact, and consistent definitions. This is particularly essential in the case of engineering terms not only technically but also financially. In a law suit, thousands of dollars might change hands because a certain term is defined in a certain way.

The work of the subcommittee on definitions of the committee on basic sciences is by no means finished. In fact it has just begun. It will take a series of several technical conferences to complete this work. The chairman is in favor of having such technical conferences scheduled for all future national conventions until the work has been completed. At the termination of this work a report will be prepared and placed in the hands of subcommittee 1 of committee 42. This will be the report of the committee on basic sciences regarding definitions which fall within its sphere of activity.

Electrical Machinery

By J. L. Hamilton, Chairman

The conference discussed three subjects, as follows:

1. The technical program for the January 1939 meeting of AIEE in so far as the electrical machinery committee is concerned was discussed.

It was generally agreed that practically the entire session be devoted to the study of temperature limits of insulation and the basis of rating of electrical machinery.

The technical program committee and the standards committee of the AIEE have approved this program and the writer has been requested to appoint a special committee to arrange for the program and to solicit representative and authoritative papers on this subject. This committee is being formed and will be announced soon.

2. It has been suggested that the electrical machinery committee consider the editing and publishing of a book which would include pertinent AIEE papers which have been presented during the last several years.

Membership—

Dear Institute Member:

These are the "dog days" of summer, the vacation period of the industry, and quite naturally Institute activities are at low ebb. New executive officers however, are taking up responsibilities and are preparing plans and programs for a year of still greater success.

Now is the time to check over the list of your friends and associates and consider which ones among them (especially among the younger men) should prepare themselves for advancement and increased responsibilities. If you know such men, speak to them today about membership. Their applications should be handed in at once, if they are to have the advantages of participation in their Section activities, commencing in a few weeks.

Yours very truly,

A. B. Cooper

Vice Chairman,
National Membership Committee

A membership proposal form appears on page 14 of the advertising section of this issue

Some members of the electrical machinery committee are of the opinion that a good bibliography of pertinent articles would be satisfactory.

After considerable discussion, it was generally concluded that compiling and editing of a book would entail a large amount of work and there would be considerable question as to whether the value of such a book would warrant the necessary work and expense.

It was also, felt that the engineering service organizations very satisfactorily cover the entire field of engineering, including electrical machinery, and that we should not endeavor to duplicate any phase of this work.

It was, therefore, agreed that the matter should be given further study to determine later at a general discussion as to whether or not any specific plans should be developed by the electrical machinery committee.

3. Some of the members present brought up for consideration the question of closer co-ordination of AIEE and ASA standardization work from the general standpoint and from the specific standpoint of transformer standards.

It was generally agreed desirable for the chairman of the electrical machinery committee to contact the AIEE representatives and the ASA, and convey to them the suggestions brought out in the discussion.

Electronics

By H. M. Turner, Chairman

There was an attendance of over 50 at this technical conference. The main subject for the meeting, the phenomenon of arcback in mercury-vapor rectifiers, was opened by W. C. White (A'23, M'30) who mentioned, among other things, that failures due to arcback are quite infrequent, about one in ten billion cycles.

The nature and various aspects of arcbacks in tank rectifiers, sealed-off pool tubes, as well as in hot-cathode tubes, was considered by the group, which joined actively in the discussion. Theories and observations were offered by those associated with tube design and research. Conditions favorable to the arcback phenomena were outlined but it was pointed out that it was difficult to produce arcbacks at will, which adds to the difficulty of experimental studies. Among the causes mentioned were lack of sufficient emission, dust on anodes, electrode disintegration, local charges accumulating near the plate which persists until the polarity reverses, and residual ionization. Some studies show that the phenomenon in the case of mercury-vapor rectifiers always occurs near the peak of the inverse cycle. Circuit effects and operating results were included by those whose experience or work had been along these lines.

It was very apparent that arcbacks are not only better understood than they were a few years ago, but are no longer a disturbing factor in rectifier operation in the field. There are still differences of opinion, however, as to the explanations of some of the observations and experiences. This fact added interest to the meeting.

Near the close of the meeting there was a discussion of tank rectifiers and hot-cathode rectifiers for large radio transmitter service, with particular reference to differences in practice between Europe and this country.

The meeting lasted more than two hours, and among others who contributed to the discussion were A. W. Hull, General Electric Company, Schenectady, N. Y.; H. E. Mendenhall and S. B. Ingram, Bell Telephone Laboratories, Inc., New York, N. Y.; O. K. Marti (A'21, M'27), Allis-Chalmers Manufacturing Company, Milwaukee, Wis.; B. K. Northrop (A'22) and W. C. Ballard (A'26) of Cornell University, Ithaca, N. Y.; D. E. Marshall (A'27, M'33), Westinghouse Electric and Manufacturing Company, Bloomfield, N. J.; Haraden Pratt (A'15, F'37), Mackay Radio and Telegraph Company, New York, N. Y.; F. E. Terman (A'23, M'34), Stanford University, Calif.; W. L. Everitt (A'25, F'36), The Ohio State University, Columbus; and M. S. Oldacre (A'13), Commonwealth Edison Company, Chicago, Ill.

Machines in Mathematical Analysis

By H. L. Hazen, Chairman

The purpose of this conference was to present before the group a picture of the broad significance of machine methods in the application of mathematical analysis to the many fields at present utilizing mathematical methods. During the past several years the appreciation of the powerful machine methods that can be produced with present techniques for carrying out mathematical processes has grown very rapidly. This applies especially to punched-card machines and to machines for solving ordinary differential equations. It appeared appropriate to the committee on basic sciences to sponsor a conference on the subject of computing and analyzing machines, with a view to bringing together those interested in this field for a presentation of the state of the art and a mutually helpful interchange of ideas.

The program consisted of three papers, a number of invited discussions, and discussion from the floor. The first paper, by Doctor Dederick was somewhat philosophical in nature and attempted to show the inherent and basic reasons why mathematics becomes so laborious in its application to certain practical problems that machine methods become economically essential if these problems are to be solved.

The second paper, by Doctor S. H. Caldwell (A'27), Massachusetts Institute of Technology, Cambridge, recounted briefly the nature and scope of the problems that have been solved by differential analyzers—machines for solving ordinary differential equations with a specific initial or boundary conditions—up to the present, and indicated briefly the field that will be open in the future to machines of this nature having greater effectiveness and scope than the present machines. This record was rather impressive by its size and importance.

The third paper, by Doctor W. J. Eckert, showed broadly how the punched-card equipment commercially developed for accounting and statistical use has been rendered useful in other fields of applied mathematics. Such equipment is of course adapted to performing given arithmetical processes on tremendous quantities of similar data.

The prepared discussions related to certain other types of mathematical machines for solving algebraic polynomials and evaluating parametric integrals, and to certain aspects of machine methods not covered in the three papers.

The field of machines for mathematical analysis is, as stated previously, growing very rapidly at the present time, and it is hoped that a wider realization of the mathematical power of these machines and the scope of their usefulness will result from the conference, as well as the stimulation of new ideas which always occurs when a group interested in a given subject get together.

Power Requirements in Electrochemical and Allied Industries

By F. O. Schnure, Chairman

This conference was attended by a small but appreciative audience. The main address, delivered by J. V. Alfriend, Jr. (A'33), a Federal Power Commission engineer, consisted of a review, on a national scale, of the electrochemical and allied industries, particularly in relation to the amount and methods of power utilization.

Mr. Alfriend's address was extremely interesting, and it is expected that the comprehensive report on these industries which the Federal Power Commission will issue in the near future, will include the data given in his address, so that it will be available for the information of all engineers in this field.

Prepared discussions by M. E. Stone, of the United Engineering and Foundry Company, and Herbert Speight (A'13, M'21) of the Westinghouse Electric and Manufacturing Company, New York, N. Y., followed.

Mr. Stone discussed the present activity in processing steel by electrolytic methods. He spoke of the power required, and the equipment used for cleaning and pickling by electrolytic methods in continuous strip mills. Important future developments in this field being the electrolytic tinning of steel strip, and cladding of steel with metals suitable for corrosion resistance.

Herbert Speight discussed the power requirements in copper refineries, pointing out the necessity in this industry for low cost power at the d-c busbars. He outlined economies which could be obtained by modernization of industrial generating plant, making the best use of waste heat steam in co-ordination with suitable boiler pressures.

Others who took part in the informal discussion included F. O. Schnure (A'23, M'35) of the Bethlehem Steel Company, Sparrows Point, Md., who commented on electrolytic steel processing; Mr. Moss of the Federal Power Commission, and N. R. Stansel (A'03, M'35), of the General Electric Company, Schenectady, N. Y., who were interested in methods of load regulation; O. A. Brown (A'30), of Iowa State College, Ames, who was interested in the possibilities of electric processing of propane gas in the manufacture of carbon black; and C. C. Levy (A'33), of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., who emphasized the wide variety of power requirements, and the high load factor of these industries.

Southern District to Meet in Miami

The Southern District meeting of the AIEE will be held in Miami, Fla., November 28–30, 1938. A program of several technical sessions, sports, trips, and entertainment is in the process of development and the location of the meeting will afford the attendants a few days of winter vacation. Headquarters will be in the Miami Biltmore Hotel at Coral Gables.

Golf, tennis, and fishing may be enjoyed at the Miami Biltmore. Annually, outstanding golf, tennis, and swimming stars gather here with national champions in these sports and their participation in the program of events adds to the entertainment of the guests. The Miami Biltmore is linked by means of a de luxe bus system of free transportation with the Florida Year-Round Clubs, at which those attending the meeting will be the guests of Henry L. Doherty (A'98, F'13), president. These clubs are the Miami Biltmore Country Club, which has two large swimming pools and beaches, an 18-hole golf course, and rows of tennis courts, the Roney Plaza Cabana Sun Club on the Ocean at Miami Beach, and Key Largo Anglers Club in the Florida Keys.

Those making arrangements for the meeting are as follows: A. P. Michaels, *chairman*, Florida Section; Joseph Weil, *secretary*, Florida Section, and the following subcommittee chairmen: W. Austin Smith, *program and papers;* J. B. Hiers, Jr., *finance;* R. Y. Pool, *entertainment;* E. F. Johnson, *hotel and reservation;* P. J. Carlin, *transportation and inspection trips;* J. D. Preston, *attendance and publicity;* and E. F. Smith, *student activities*.

Lightning Arrester Subcommittee Meets

The following report was provided by J. R. North (A'21, M'29), Commonwealth and Southern Corporation, Jackson, Mich., chairman of the subcommittee on lightning arresters of the AIEE committee on protective devices.

The lightning arrester subcommittee held its final meeting of the year during the summer convention (with 11 of 14 members represented) to discuss the progress made on the various projects since the January 1938 meeting.

Considerable interest is being shown throughout the industry in the procedures developed for testing line-type and station-type arresters in the field. Herman Halperin (A'21, M'26), Commonwealth Edison Company, Chicago, Ill., reported the results obtained by numerous companies in testing distribution arresters in accordance with the practices outlined in the report "Testing and Application of Lightning Arresters" (AIEE technical paper 38-43). H. W. Collins (A'22), The Detroit Edison Company, Detroit, Mich., submitted a memorandum outlining the procedure for use in testing particular types of station arresters. It was decided that this work should be continued.

The characteristics of high-voltage line-type arresters have been presented in the committee report "Line-Type Lightning Arrester Performance Data" (AIEE technical paper 38-56). Arrangements were made to continue this work and prepare a similar report covering station type arresters for presentation next year.

A preliminary report of the proposed standards on protector tubes was presented for consideration. This represents the first step toward the formulation of a comprehensive standard covering these devices.

H. R. Stewart (A'26), New England Power Service Company, Boston, Mass., reported on a survey of the industry made during recent months regarding the present Institute lightning arrester standards number 28 and the necessity and desirability of revising them. It was definitely the consensus of opinion that these standards should be revised and it was recommended that this work be undertaken next year.

It is also proposed to study protection problems for specific types of apparatus, including rotating machines, constant-current transformers, induction voltage regulators, short lengths of cables, potheads, and pole-top switches.

In discussing future Institute papers, it was tentatively felt that the subcommittee should sponsor a paper on "Testing Line Type Arresters" by Mr. Halperin and a subcommittee report on protector tubes.

Detroit-Ann Arbor Section Becomes Michigan Section

Upon recommendation of the AIEE Sections committee, the Institute's board of directors has authorized a change in name of the Detroit-Ann Arbor Section to "Michigan Section," but no change in Section territory will be involved.

The Detroit-Ann Arbor Section was organized January 13, 1911. Newly elected officers of the Michigan Section for the term 1938–39 are: *chairman*, R. E. Greene (A'26) senior engineer in the engineering division, The Detroit Edison Company; *secretary*, W. G. Knickerbocker (A'20, M'30) assistant superintendent of meters, The Detroit Edison Company.

CIGRE Representatives Visiting U.S. Industries

A party of distinguished foreign visitors including 12 engineers and others constituting an official delegation of the International Congress of Large High Tension Systems (Conference Internationale des Grands Reseaux Electriques—called CIGRE for short), entered the United States in time to attend the AIEE summer convention in Washington, D. C. June 20–24 inclusive, and since has been touring the country visiting various electrical manufacturing plants and electric power systems. A series of events arranged for this party in Washington during the convention week included a round-table technical conference, an informal reception at the French Embassy, numerous luncheons and inspection trips, and attendance at convention functions.

Participating in the round-table technical conference were the following official CIGRE delegates:

Pierre Prache (A'33), chief engineer, Ateliers de Constructions Electriques de Jeumont, Paris.

Roger Dubusc, chief of the laboratory of measuring apparatus, Fabrication des Compteurs, Paris.

Rene Caizergue, chief of dispatching service, Union d'Electricité, Paris.

Jacques d'Harcourt, director, Société Inter-Paris, Paris.

Thomas Boveri (A'27, M'34), managing director, Brown Boveri and Co., Ltd., Baden, Switzerland.

François Cahen, chief of electric research, Société Alsthom, Paris.

Karel Novak, representative, l'Association des Electriciens Tchecoslovaques, Paris.

Robert Marny, consulting engineer, representing The Association des Electriciens Tchecoslovaques, Paris.

J. Rosen, director, Parsons and Co., Newcastle-on-Tyne, England.

Louis Astier, chief engineer, C.P.D.E., Paris.

Among others comprising the visiting group were:

Marcel Combasson, director, l'Electricité de Marseille, Marseille, France.

Jean Rey du Boissieu, assistant chief engineer of commercial service, l'Est-Lumiere, Paris.

Jean Clopin, commercial director, Société Calor, Lyon, France.

Dominique Denis, chief engineer, Société Parisienne pour les Chemins de Fer et Tramways Electriques, Paris.

Jean Ricard, chief of testing service, l'Union d'Electricité, Paris.

Pierre Delattre, technical director, Cie Nationale du Rhone, Lyon, France.

Fernand Montois, engineer, Société d'Electricité de Paris, Paris.

Max Wurmser, principal engineer, Compagnie Parisienne de Distribution d'Electricité, Paris.

Pierre Gires, chief engineer, The Société d'Electricité de la Region Valenciennes-Anzin, Valenciennes, France.

Arrangements for the visitors were made by a committee organized by Frederic Atwood (M'27) of New York, CIGRE vice president for the United States, with F. A. Allner (A'12, M'14) of Baltimore, Md. as chairman.

ASTM Elects Officers. At the first session of the annual meeting of the American Society for Testing Materials, June 28, 1938, election of the following officers for 1938–39 was announced: *president*—T. G. Delbridge, manager of the research and development department, The Atlantic Refining Company, Philadelphia, Pa.; *vice-president*—W. M. Barr, chief chemical and metallurgical engineer, Union Pacific Railroad company, Omaha, Nebr.; *members of executive committee*—A. T. Goldbeck, engineering director, National Crushed Stone Association, Inc., Washington, D. C., Dean Harvey (A'04, M'14) materials engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., G. E. Hopkins, technical director of the Bigelow-Sanford Carpet Company, Inc., Thompsonville, Conn., Allen Rogers, supervisor of the course in industrial chemical engineering, Pratt Institute, Brooklyn, N. Y., and J. J. Shuman, inspecting engineer, Jones and Laughlin Steel Corporation, Pittsburgh, Pa.

New Requirements for Fellow Grade Now in Effect

On July 21 a revision of the Constitution of the Institute took effect, bearing solely on requirements for the grade of Fellow. With two exceptions, the Fellow grade henceforth is open only to those who have been affiliated with the AIEE in good standing in the grade of Member for a period of at least five years immediately preceding the date of application for transfer. In addition, and with the same two exceptions, applications for Fellow must originate by proposal of five other Fellows or Members. All Fellow applications must comply, exactly as heretofore, with the requirements calling for the submission of detailed professional records and five Fellow references. The two exceptions previously mentioned are contained in clauses "c" and "e" of Section 4, Article II. Provision is made there for the entrance to Fellow grade either directly or through transfer, free of the proposal or previous affiliation requirements, of foreign engineers of standing equivalent to Fellow, as well as those who may have become pre-eminent by virtue of notable original work in electrical science.

To comply with the new requirements of clauses "a," "b," and "d," Fellow applications must be transmitted to headquarters accompanied by communications (letters, or regular forms provided by headquarters) signed by five Fellows or Members proposing the applicants for Fellow. Applications made under clauses "c" and "e" can be either applications for admission to Fellow or transfers from a lower grade, and no proposal requirement is involved.

As pointed out at the time of the submission of the constitutional changes to ballot, the new restrictions on Fellow grade were drawn up in compliance with a strong feeling that had made itself evident over a period of many years—a feeling that the Fellow grade should be in the nature of an award to those engineers who had reached a pre-eminent position through technical accomplishments in the electrical field and who had shown an interest in the welfare of the profession through affiliation with the Institute. At the same time it was realized that there were certain exceptions for which it was desirable to provide; hence clauses "c" and "e."

The changes have received official approval by ballot of the membership (*EE July, p. 303*), and now will be put to test. It is hoped they will accomplish the desired result.

International Testing Congress Proceedings. Proceedings of the 1937 Congress of the International Association for Testing Materials held in London, England, has been issued. The publication includes the more than 200 papers presented and ensuing discussions. Copies, in cloth binding, may be obtained from the secretary of the congress, K. Headlam-Morley, The Iron and Steel Institute, 28 Victoria Street, London, S. W. 1, England, at $7.75 each; this price includes prepayment of postage

Future Meetings of Other Societies

American Association for the Advancement of Science. Winter meeting, December 27–31, Richmond, Va.

American Gas Association. October 10–14, Atlantic City, N. J.

American Physical Society. 223d meeting, November 25–26, Chicago, Ill.

American Society of Mechanical Engineers. Fall meeting, October 5–7, Providence, R. I.

Illuminating Engineering Society. Annual convention, August 29–September 1, Minneapolis, Minn.

International Congress of Applied Mechanics. September 12–16, Cambridge, Mass.

National Electrical Contractors Association. September 12–15, Detroit, Mich.

National Electrical Manufacturers Association. October 24–28, Palmer House, Chicago, Ill.

National Safety Council. October 10–14, Stevens Hotel, Chicago, Ill.

Society of Automotive Engineers. Sectional regional tractor meeting, September 8–9, Minneapolis, Minn.

National regional fuels and lubricants meeting, October 6–7, Tulsa, Okla.

National aircraft production meeting, October 13–15, Los Angeles, Calif.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Usefulness of Mathematics in Engineering

To the Editor:

Mr. C. J. Holslag's letter in the May 1938 issue of ELECTRICAL ENGINEERING on "Preparation of Manuscripts" calls for comments particularly since he himself invites them.

In the first place it is asserted that the journal publishes as first and foremost school and college papers. A review of ELECTRICAL ENGINEERING for the year 1937 shows that 165 papers were published. Of these, 119 or over 72 per cent came from industry; 42 or over 25 per cent came from colleges, and 4 or about 2.5 per cent were joint papers in which industry and the colleges co-operated. Does this show that college papers are first and foremost?

As to the "mathematical fairy tales," Mr. Holslag might be interested to observe that industry tells them just as tall as the professors do. To convince himself of this fact let him review some of the mathematical papers published by men in the industry such as ELECTRICAL ENGINEERING, volume 56, 1937, pages 27–31, 49–58, 91–100, 333–8, 344–6, etc., etc. Apparently some industries feel that mathematics is useful to them, otherwise they would not allow their men to "waste their time" on these mathematical papers.

Truly nobody is aking Mr. Holslag to believe anything about the electron theory of matter. But there seems to be more fact to it than to the assertions he makes in his letter.

Very truly yours,

M. G. MALTI (M'34)

(Assistant Professor of Electrical Engineering, Cornell University, Ithaca, N. Y.)

To the Editor:

Referring to Mr. Holslag's letter on page 230 of the May 1938 issue, Doctor Pupin once summarized one of his discussions in a sentence that I remember thus: "After you get the physical facts in mind it is easy enough to find the mathematics to prove them." Later he said, if I understood his lowered voice correctly, that he worked out the mathematical theory for his loading coils after he had everything else complete, and did so at all only for sales purposes; he had been obliged to prove the facts to the telephone engineers by mathematics before they would give his unorthodox ideas any consideration. This adds to Holslag's comments on Pupin.

In my opinion, mathematics is a set of tools; and the larger and better the set an engineer has, the better prepared he is to attack any problem that comes to him, other matters being equal. Nevertheless, the prime function of mathematics itself, as distinguished from mathematical training in logical habits of thought, is service. For a tool to give service it must have a workman who knows what he wants to do, as well as knowing how to use the tool. Spending study time in memorizing elaborate mathematical proofs of physical facts and spending recitation and lecture periods in copying differential equations from the board, to my mind, is begging the essential problem. To my knowledge some universities in the East and also in the West are requiring students to do just about these things, instead of giving them clear physical concepts of physical facts, with the result that the ideas of Doctor Michael Pupin, Doctor William Suddards Franklin, and Doctor Carl Hering, to mention only a few of those

to whom I have listened in class or in public lecture, are going to the discard. For a decade or more I have asserted with pleasure that the engineering graduate of recent years usually has a better command of English than the average of my day. In contrast, however, his mental pictures of physical facts that he knows only as sets of equations on page so and so are often hazy at best and sometimes are not entirely correct. The natural result is papers and textbooks that give excellent examples of English and mathematical decoration but are marred by misconceptions or outright mistakes in physical fact.

Holslag's letter, it seems to me, is somewhat overdrawn, even if we omit the wide field of mathematical physics. Yet it does not go to the root of the trouble, if my experience and observation may be trusted. The primary fault is not exhibition mathematics in published papers and texts but rather is the method of instruction now current in some prominent universities. Some authors of unnecessary mathematics are merely following training and example.

Nevertheless, in a certain university a researcher did not search the pertinent *mathematical* literature, apparently never had heard of statistical results and the probability curve, and published findings that were wholly wrong because he averaged readings for factors that were unrelated! Even simple arithmetic tells us to break down products into prime factors, a step that this researcher omitted.

These opposing incidents show that both sides of a narrow road permit a driver to get off it, especially when the road is not well defined.

Very truly yours,

HENRY HENDRICKS KETCHAM (A'13, M'23)

(8 West Church Street, Bethlehem, Pa.)

To the Editor:

The letter "Preparation of Manuscripts" published in the May 1938 issue is pertinent to discussions of socialization of engineering education. It presents the human, the commonsense view which must hold in such matters.

Lately it has become fashionable to accept two statements: (1) Science (and thus engineering) is a major cause of present socio-economic distress. (2) An increased application of scientific method to the interests of men must perfect a scheme to bring humanity back from the abyss toward which unthinking devotion to the machine has lead the way.

Unfortunately, as working hypotheses for improving the state of society, neither of these statements can serve. Reliance on the mystical benignities of old-fashioned business and the higher salesmanship is what has got us to where we are. As to whether the "methods" of science will be permitted gratuitously to drag society from its self-made chaos, Mr. Holslag's letter gives more than a gentle hint.

I sincerely trust further comments will be received.

Very truly yours,

J. ANDREW DOUGLAS (A'18, M'29)

(Physics and General Science Teacher, Murphy High School, Mobile, Ala.)

Journals for Electrical Engineers

To the Editor:

The article in the March 1938 issue of ELECTRICAL ENGINEERING by Charles F. Dalziel concerning "Journals for Electrical Engineers" indicates that the task of keeping fully abreast of the advances which are reported in the literature of electrical engineering is a large one. It has occurred to me that Mr. Dalziel's article could serve as a starting point for some simplification of the task.

Of the total number of 20 basic journals from which Mr. Dalziel's reference counts were made there were eight which are journals of physics rather than engineering. It seemed to me that references taken from these journals would not be to engineering work, nor to physics which is a direct foundation of engineering. Consequently, I made new totals, omitting the references from the following journals: *Proceedings* of the Physical Society, *Philosophical Magazine, Journal* of the Franklin Institute, *Physical Review, Comptes Rendus, Physikalische Zeitschrift, Zeitschrift für Physik.* These totals I have arranged in graphical form, grouping English language journals together in one graph, and foreign language journals together in another graph as did Mr. Dalziel. However, I have not included in my lists any journals, the contents of which are listed by the American Institute of Physics in the "Current Literature of Physics" section of its journals. These were omitted because it is my suggestion that ELECTRICAL ENGINEERING undertake the publication in a similar manner of the titles of current articles that appear in a selected group of engineering journals. Such a listing would enable one to review contemporary engineering literature very quickly. It would not replace the abstract journals, but would provide a prompt and easily available source of reference.

The selection of journals to be listed would naturally be governed to a great extent by the wishes of the readers of ELEC-

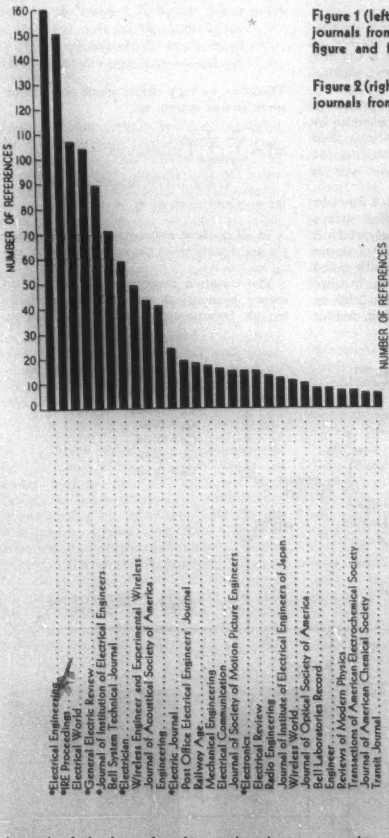


Figure 1 (left). References to English-language journals from journals marked * on both this figure and figure 2, omitting self-references

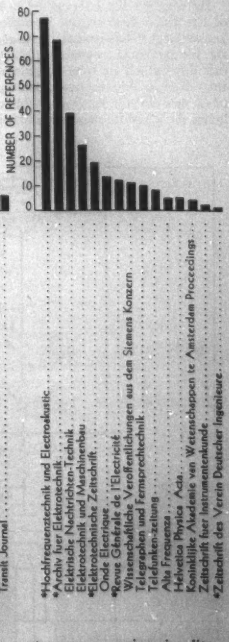


Figure 2 (right). References to foreign-language journals from journals marked * on figure 1, omitting self-references

TRICAL ENGINEERING, but perhaps my graphs could give a preliminary selection. I have indicated a selection of 18 English and ten foreign-language journals, which seem to me to cover the ground fairly well, but which is, of course, an arbitrary one and is given primarily to serve as a basis for discussion.

Very truly yours,

GEORGE B. HOADLEY (A'35)

(Instructor in Electrical Engineering, Massachusetts Institute of Technology, Cambridge)

What Is Tensor Analysis?

To the Editor:

I have read with much interest and pleasure "What Is Tensor Analysis?" by Doctor Banesh Hoffmann and his article is the best elementary analysis of the subject which I have seen.

His development of the Pythagarean interval $ds^2 = dx^2 + dy^2$ into a geodesic by testing it by translation, rotation, their combination, stretching, and changing the angles between the co-ordinate axis is unique and brilliant.

He employs the interval ds^2 as a function of the basic vector $(dx)^i$ identified with a geometrical displacement in space, which is the fundamental measure number of tensor calculus, which in turn is generally called the absolute differential calculus, because $(dx)^i$ was considered from 1905 to 1928 as being the absolute measure number, and for beginners Doctor Hoffmann's application is perfect.

If this system of space were linear and non-Euclidian in one direction only we would write the interval ds^2 as

$$ds^2 = g_{11}dx_1^2 \qquad (1)$$

If space were considered to be of 2 dimensions, equation 1 becomes

$$ds^2 = g_{11}dx_1^2 + g_{22}dx_2^2 + 2g_{12}dx_1dx_2 \qquad (2)$$

In three-dimensional space we would write:

$$ds^2 = g_{11}dx_1^2 + g_{22}dx^2 + g_{33}dx^2 + 2g_{12}dx_1dx_4 + 2g_{13}dx_1dx_3 + 2g_{23}dx_2dx_3 \qquad (3)$$

And in 3 + 1-dimensional space (Einsteinian) equation 1 becomes

$$ds^2 = g_{11}dx_1^2 + g_{22}dx_2^2 + g_{33}dx_3^2 + g_{44}dx_4^2 + 2g_{12}dx_1dx_2 + 2g_{13}dx_1dx_3 + 2g_{14}dx_1dx_4 + 2g_{23}dx_2dx_3 + 2g_{24}dx_2dx_4 + 2g_{34}dx_3dx_4 \qquad (4)$$

Therefore we may define space of n dimensions in this system as:

$$ds^2 = \sum_1^m \sum_1^n \left[g_{mn}dx_n^2, (m = n = 1, 2, 3 \ldots) + 2g_{mn}dx_m dx_n \times (m \neq n \text{ and } m < n;\ m, n, = 1, 2, 3, \ldots) \right]$$

In all of these symmetrical equations the g's are functions of the co-ordinates $x_1, x_2, x_3, x_4 \ldots$.

The common conception of space is an empty geometrical space. This is wholly untrue, because space in fact is the domain of the probability distribution of a particle. In other words we have learned that it is an essential characteristic of space that it is either occupied, or at least that it, at the present, has a finite probability of being occupied.

The form of the right-hand side of the above equations corresponds to the reality of observation, but our left hand measure number, ds^2 is in fact merely a convention. The above equations report ds^2 to be some quadratic function of the differences of the chosen co-ordinates.

Just ten years ago an additional and different measure number to ds^2 was presented by P. A. M. Dirac when he introduced his four-valued wave tensor ψ in his unsymmetrical equation which also is invariant to translation, rotation, and to the Lorentz transformation.

Further study of ψ has now shown that our previously considered "absolute" measure number ds^2 is merely a special case of the latter, even as Euclidean space is a special case of Einstein's 3 + 1 space. Neither ds^2 nor Dirac's four-valued wave tensor ψ can be accepted in the present state of our knowledge as our ultimate measure number in the absolute sense.

Very truly yours,

CLARENCE E. ROSE (M'34)

(Senior Engineer Examiner, United States Public Works Administration, Washington, D. C.)

Electronic Switching Circuits

To the Editor:

We read with much interest the article in the May 1938 issue of ELECTRICAL ENGINEERING entitled "Some Electronic Switching Circuits," by C. C. Shumard. We should like very much to discuss one feature of this paper. We developed an impulse-voltage generator somewhat similar in principle to that described in figure 6 of Mr. Shumard's article. We arranged the circuit as indicated in figure 1 of this letter. By supporting the type-34 linearity tube on porcelain insulators, together with its filament and screen-biasing batteries, we were able to reduce the capacitance until we could get a voltage impulse lasting one microsecond. We were not able to reduce the time of the impulse below this minimum figure. Mr. Shumard states that with the assumed values of resistance and capacitance the minimum impulse interval should be 1/4 microsecond. We attempted to use a circuit like that described in figure 6a of his article, but found that the capacitance between ground and the anode side of the type-885 tube was too great to obtain the impulse duration mentioned. We should like very much to know if Mr. Shumard was successful in obtaining an impulse of 1/4 microfarad duration. If he obtained this low time interval, we should like to know what special provisions, if any, he made in the design of the sweep circuit.

Very truly yours,

H. A. BROWN (A'16, M'26)
P. W. RYBURN

(Department of Electrical Engineering, University of Illinois, Urbana)

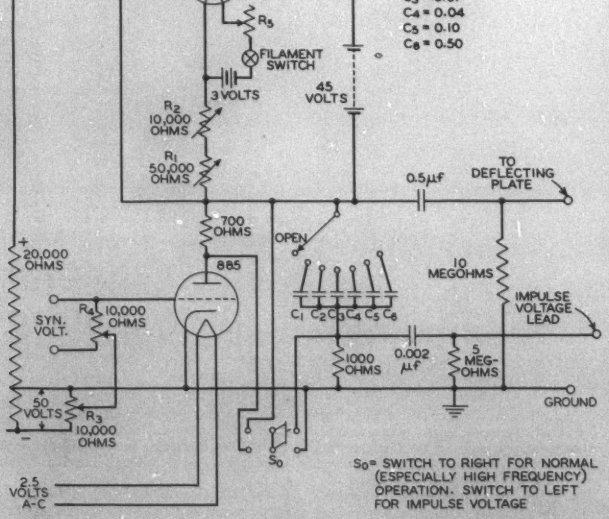


Figure 1

Personal Items

F. E. Johnson (A'13, F'31) has been appointed dean of the college of engineering of the University of Wisconsin, Madison. Since 1935 dean of the college of engineering of the University of Missouri, Dean Johnson was born May 27, 1885, at LeRoy, Mich., and received the degrees of bachelor of arts (1906) and electrical engineer (1909) at the University of Wisconsin. Following a period of employment in substation construction work in the western part of the United States and Canada, he was appointed instructor in electrical engineering at The Rice Institute, Houston, Texas, in 1912. Dean Johnson was appointed instructor in electrical engineering at the University of Kansas in 1915, and became successively assistant professor, associate professor, and professor of electrical engineering. In 1928 he was appointed head of the department of electrical engineering; however, he resigned in the same year to become head of the department of electrical engineering at Iowa State College, Ames. A director of the Institute, Dean Johnson has served during the year just ending as a member of the Institute's committee on education, electrical machinery, and membership; and as chairman of the committee on student branches. He is Institute representative on the Engineers' Council for Professional Development.

J. W. Dawson (M'35) has received the AIEE national prize award for best paper in engineering practice for his paper "New Developments in Ignitron Welding Control." Mr. Dawson was born at Sumner, Iowa, in 1901, and was graduated from Iowa State College in 1926 with the degree of bachelor of science in electrical engineering; in 1938 he received the degree of master of science from the University of Pittsburgh. In 1926 he became affiliated with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., as student engineer, and from 1927 until 1937 he was employed continuously in the engineering department of that company. Early in 1938 he left the employ of the Westinghouse company to become research and development engineer for the Raytheon Production Corporation, Newton, Mass. During the year just ending Mr. Dawson has been a member of the Institute's committee on electric welding and the joint subcommittee on electronics.

R. W. Warner (M'28) has become professor and head of the department of electrical engineering at the University of Texas, Austin. Professor Warner is a native (1889) of Freeport, Ill. He was graduated from Washburn College with the degree of bachelor of arts, later attending the University of Kansas and receiving there the degrees of bachelor of science in electrical engineering (1918) and electrical engineer (1928). After holding various positions Professor Warner became assistant to the chief engineer of the Topeka Edison Company, Topeka, Kans., in 1920, but in the following year was appointed instructor in electrical engineering at the University of Kansas. In 1922 he became instructor in electrical engineering at the University of Wisconsin, but remained only one year before becoming affiliated with the General Electric Company, Schenectady, N. Y. Professor Warner became an engineer for the Kansas City (Mo.) Power and Light Company in 1924 and held that position until he returned to the University of Kansas as assistant professor of electrical engineering in 1928. In the following year he was promoted to associate professor, and in 1929 he received his professorship. Since 1936 he has been head of the department of electrical engineering. During 1935–36 he served as an exchange professor of electrical engineering at Massachusetts Institute of Technology.

Reuben Reiter (A'36) has been awarded the AIEE national prize award for best paper in theory and research with C. L. Dawes (A'12, F'35), co-author of the paper "Electrical Characteristics of Suspension-Insulator Units." A native of London, England, Doctor Reiter attended Harvard University and received the degrees of bachelor of science in electrical engineering and business administration and doctor of science, the last degree in 1935. From 1931 until 1935 he was research assistant and part-time instructor at Harvard. Doctor Reiter at present is engaged in consulting work for several small sound and music companies, and is technical director of research at the New York Institute for the Education of the Blind, New York, N. Y.

E. O. Shreve (A'06) recently became the first recipient of the Marston medal, an award initiated in 1938 by Iowa State College to honor outstanding achievement in engineering by its alumni. Mr. Shreve was graduated from Iowa State College in 1904 with the degree of bachelor of science in electrical engineering, following which he became associated with the General Electric company as a student engineer. In 1906 Mr. Shreve was sent to San Francisco, Calif. as a supply salesman, and in the following year was assigned to the company's Nevada territory. In 1909 he was recalled to San Francisco as turbine specialist and two years later was made apparatus salesman in charge of sales to the Pacific Gas and Electric Company, successively becoming manager of apparatus sales, assistant manager of the San Francisco office, and manager of that office. Later Mr. Shreve was sent to Schenectady, N. Y., as manager of the industrial department of the General Electric Company and shortly thereafter was elected an assistant vice-president. In 1934 he was elected vice-president in charge of sales, the position he now holds.

Sterling Beckwith (A'34) has received honorable mention in the AIEE national prize awards for best paper in engineering practice for his paper "Approximating Potier Reactance." A native (1906) of Carthage, Mo., Mr. Beckwith was graduated from Stanford University in 1927 with the degree of bachelor of science in electrical engineering. In the same year he entered the student training course of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., later attending the design school of that company for six months and then joining the power engineering department. In 1929 he received the degree of master of science from the University of Pittsburgh in pursuing the co-operative course of study with the Westinghouse company. In 1931 he was awarded a teaching assistantship in the electrical engineering department of California Institute of Technology. He received the degree of doctor of philosophy at that Institution in 1933, then worked for two years as junior engineer with the Metropolitan Water District of Southern California. In 1935 Mr. Beckwith went to Milwaukee, Wis., to join the electrical department of the Allis-Chalmers Manufacturing Company.

John Murphy (A'00, F'13) recently retired from active service. During the last four years Mr. Murphy has been acting superintendent of the Rideau Canal, and has a record of 32 years of service with the Department of Transport and Board of Railway Commissioners, Ottawa, Ont., Canada. Born in Ottawa in 1868, Mr. Murphy was graduated from the University of Ottawa in 1884. Three years later, when the Chaudiere Electric Light and Power Company was established, he was placed in charge

J. W. DAWSON

REUBEN REITER

F. E. JOHNSON

of the company. In 1891 the Ottawa Electric Railway Company was formed and Mr. Murphy was placed in charge of the power plant of both the new company and of the Chaudiere company. He was associated with those companies for 20 years and concurrently conducted his own consulting engineering practice. Mr. Murphy was president of the Canadian National Committee of the International Electrotechnical Commission from 1927 until 1937, and was official delegate to the World Power Conferences in 1924 and 1930.

E. W. Schilling (A'29, M'33) recently became head of the department of electrical engineering at Montana State College, Bozeman. A native (1897) of What Cheer, Iowa, Doctor Schilling attended the University of South Dakota and the University of Illinois, receiving the degree of bachelor of science in electrical engineering at the latter school in 1919. From Iowa State College he received the degrees of master of science in electrical engineering (1930), doctor of philosophy (1933), and electrical engineer (1936). After holding various industrial positions Doctor Schilling became instructor in electrical engineering at Iowa State College in 1920. Three years later he established the consulting engineering firm of E. W. Schilling and Company, Brandon, S. D., but in 1928 returned to his previous position on the faculty of Iowa State College. In 1931 he was appointed assistant professor of electrical engineering at Michigan College of Mining and Technology, Houghton, being advanced to the position of associate professor in 1934. Doctor Schilling is author or coauthor of several papers presented before the Institute.

W. M. Skiff (A'07, M'33) has retired as manager of the Nela Park engineering department of the General Electric Company, Cleveland, Ohio, a position he has held since 1930. Mr. Skiff was born in 1883 at Jamestown, N. Y., and was graduated from the Case School of Applied Science with the degrees of bachelor of science (1906) and electrical engineer (1930). Following his graduation in 1906 he became affiliated with the engineering department of the National Electric Lamp Association and in the following year was appointed office manager of the Association. In 1912, when that organization became a part of the General Electric Company, he was appointed manager of the engineering department of the National Lamp Works. In 1930 the engineering department of the National Lamp Works and the Edison Lamp Works were combined with the Nela Park engineering department of the General Electric Company, and Mr. Skiff was appointed manager of the consolidated departments.

H. H. Skilling (A'28, M'34) has received the AIEE Pacific District prize for best paper with P. deK. Dykes, co-author of the paper "Distortion of Traveling Waves by Corona." Doctor Skilling is assistant professor of electrical engineering at Stanford University, Calif., from which he received the degrees of bachelor of arts (1926), engineer in electrical engineering (1927), and doctor of philosophy (1931). In 1930 he was awarded the master of science degree by Massachusetts Institute of Technology. From 1927 until 1929 Doctor Skilling was employed in the construction department of the Southern California Edison Company. Since 1929, except for the period of graduate study at MIT, he has been a member of the electrical engineering faculty of Stanford University. He has presented several papers on power transmission before the Institute.

Shiv Narayan (A'10, M'13) has been appointed principal of the college of engineering, Poona, India. Professor Narayan was born at Delhi, India, in 1883, and received the degrees of bachelor of science and master of arts at Forman Christian College (Lahore, India) and Government College, respectively. Later he came to the United States and received the degree of bachelor of engineering in electrical engineering at Union College in 1909. Following his graduation from Union College he returned to India and for three years held various positions with electric power companies. In 1913 he was appointed assistant professor of electrical engineering in the Poona College of Engineering, eventually becoming professor of electrical engineering and physics. Professor Narayan has written several books on hydroelectric power plants in India and on electrical machinery.

E. O. Lunn (A'32) has received the AIEE Canada District prize for best paper and prize for initial paper for his paper "Induction Motors Under Unbalanced Conditions." Mr. Lunn is engineer for the Peterson and Cowan Elevator Company, Ltd., Vancouver, B. C., Canada. A native (1909) of Albert, N. B., Canada, he was graduated from the University of British Columbia in 1930 with the degree of bachelor of applied science in electrical engineering. Following his graduation he entered the student training course of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., but shortly thereafter became electrical engineer for the Turnbull Elevator Company, Toronto, Ont., Canada, where he remained for almost five years. He has been associated with the Peterson and Cowan Elevator Company during the last three years.

W. T. Thomson (A'37) has received the AIEE Pacific District prize for initial paper for his paper "Resonant Nonlinear Control Circuits." Mr. Thomson was born in Kyoto, Japan, in 1909, and received the degrees of bachelor of science in electrical engineering (1933) and master of science in electrical engineering (1934) at the University of California. During 1935–36 he was a teaching assistant in physics and mathematics at the University of California agricultural college at Davis, and in the same year was assigned to a research project on solar radiation at that institution. During 1936–37 he was a university fellow in electrical engineering at the Berkeley branch of the University of California. He now is instructor of applied mechanics at the Kansas State College of Agriculture and Applied Mechanics, Manhattan.

C. F. Hirshfeld (A'05, F'36) has been granted the honorary degree of doctor of engineering by the University of Detroit. According to the citation, Doctor Hirshfeld "has led a movement to liberalize and humanize the engineering profession by advocating in it not only the highest technical knowledge and skill, but also a broad general culture and a sense of social and civic responsibility . . . . . to permit those worthy purposes, has been the first chairman and constant guide and leader of the Engineers' Council for Professional Development, an organization which has already in six brief years greatly enhanced the dignity of the engineering profession and more particularly, the academic value of engineering education." Doctor Hirshfeld is chief of research of the Detroit Edison Company and past chairman of ECPD.

A. L. Samuel (M'34) recently received the prize of the Institute of Radio Engineers for the best paper published in the IRE *Proceedings* during 1937. Mr. Samuel was born in 1901 at Emporia, Kans., and was graduated from the College of Emporia with the degree of bachelor of arts in 1923. He then enrolled in Massachusetts Institute of Technology and received there the degrees of bachelor of science in electrical engineering (1925) and master of science in electrical engineering (1926). During the time he attended Massachusetts Institute of Technology he was employed in various positions by the General Electric Company. Following his graduation in 1926 he served for two years as instructor in electrical engineering at MIT, and since 1928 has been a member of the technical staff of the Bell Telephone Laboratories, New York, N. Y.

C. F. Dalziel (A'33) has been promoted to assistant professor of electrical engineering at the University of California, Berkeley. Professor Dalziel is a native (1904) of San Francisco, Calif., and received the degrees of bachelor of science (1927), master of science (1934), and electrical engineer (1935) at the University of California. He was employed by the General Electric Company and the San Diego Consolidated Gas and Electric Company prior to joining the faculty of the University in 1932. He is the author of a paper "Static Power Limits of Synchronous Machines," scheduled to be presented at the AIEE pacific coast convention, Portland, Ore., August 9, 1938.

J. L. C. Löf (Enrolled Student) has received the AIEE North Central District prize for Branch paper for his paper "The Efficiency of Small Electric Motors." Mr. Löf is a native of Denver, Colo., and was graduated from the University of Denver with the degree of bachelor of science in electrical engineering in June 1938.

M. B. Wyman (A'30, M'35) has been transferred to East Pittsburgh, Pa., as manager of the district engineering department of the Westinghouse Electric and Manufacturing Company. Mr. Wyman formerly was engineering manager of the southwestern district of the Westinghouse company, with offices at St. Louis, Mo.

H. C. Sutton (A'10, M'17) has been elected president of the Association of American Engineers in Cuba. Mr. Sutton is a native of Philadelphia, Pa., and a graduate of Cornell University in mechanical and electrical engineering. For several years he was associated with the United Gas Improvement Company of Philadelphia, of which organization he was chief engineer from 1927 until 1930. Since 1930 he has been chief engineer of the Cuban Electric Company, a subsidiary of the American and Foreign Power Company, with headquarters in Havana.

F. I. Morgan (A'31) has received the AIEE Middle Eastern District prize for initial paper for his paper "An Electrical Governor." Mr. Morgan was born in 1889 at Linwood, N. Y. In 1909 Mr. Morgan became affiliated with the Genesee Light and Power Company, Batavia, N. Y., remaining there until 1914, when he joined the Schenectady Power Company. Since 1915 Mr. Morgan has been employed by the Pennsylvania Water and Power Company, for several years at Holtwood, Pa., and more recently as maintenance engineer at Baltimore, Md.

M. G. Lloyd (A'08, F'12) recently was elected president of the Washington (D. C.) Safety Society. Doctor Lloyd is chief of the section of safety codes, National Bureau of Standards, Washington, D. C., and is representative of the Department of Commerce upon the Federal Interdepartmental Safety Council. During the year just ending he has been a member of the Institute's committee on safety; he is also past chairman of the AIEE Washington Section.

W. L. Enfield (A'10, F'32) recently received the degree of doctor of engineering from Kansas State College of Agriculture and Applied Science. The degree was granted to Mr. Enfield "in recognition of the outstanding service he has rendered in the advancement of lighting progress." Since 1914 Mr. Enfield has been manager of the lamp development laboratory in the incandescent lamp department of the General Electric Company, Cleveland, Ohio.

J. F. Porter (A'87, F'33) recently received the Chicago alumni merit award given by the Chicago Alumni Association of Iowa State College. The award was granted "in recognition of outstanding service and contributions to humanity." Mr. Porter, who is chairman of the board of directors of the Kansas City (Mo.) Power and Light Company, was graduated from Iowa State in 1884.

B. R. Prentice (A'35) has received the AIEE North Eastern District prize for initial paper for his paper "Fundamental Concepts of Synchronous Machine Reactances." Mr. Prentice received honorable mention in the 1937 AIEE national prize awards for the same paper, as announced on page 324 of the July 1938 issue of ELECTRICAL ENGINEERING.

Dean Harvey (A'04, M'13) has been elected a member of the executive committee of the American Society for Testing Materials for the two year term 1938–40. Since 1911 Mr. Harvey has been materials engineer in the central material and process engineering department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and has been active in committee work of ASTM.

C. J. Wells (M'37) has become Western regional electrical engineer for the United States National Park Service (erroneously reported in the May 1938 issue as United States Irrigation Service), with headquarters at Santa Fe, N. M. Mr. Wells formerly was electrical engineer for the United States Irrigation Service at Coolidge, Ariz.

Alex Dow (A'93, F'13, HM'37) recently received the honorary degree of doctor of arts in business administration from Wayne University. AIEE Edison medalist in 1936, Doctor Dow has received several other honorary engineering degrees. He is president of the Detroit (Mich.) Edison Company.

F. H. Travers (A'26, M'32) has been appointed electrical engineer in the State Department of Public Works, Hartford, Conn. Mr. Travers formerly was employed in the wiring device engineering department of the General Electric Company, Bridgeport, Conn.

M. G. Lewis (A'36) has become junior electrical engineer for the Golden Gate International Exposition, San Francisco, Calif. Mr. Lewis formerly was electrical engineer for the University Electric Company, Santa Clara, Calif.

A. LeG. Ritter (A'33) has been appointed an inspector for the Federal Communications Commission, San Pedro, Calif. Formerly Mr. Ritter was a radio engineer for station KHJ, Don Lee Broadcasting Company, Los Angeles, Calif.

A. W. Robertson (A'27) has been elected to the board of directors of the National Association of Manufacturers. Mr. Robertson is chairman of the board of the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.

J. C. Stevens (A'20, M'30) recently received the honorary degree of bachelor of engineering from Oregon State College. Doctor Stevens is a consulting engineer in the firm of Stevens and Koon, Portland.

L. M. Smith (A'35) recently became an engineer for The Lane-Wells Company, Vernon, Calif. Mr. Smith has been an engineer for the General Electric Company, Ontario, Calif.

G. J. Amorosi (A'34) has become a draftsman for the Cole Electric Products Company, Inc., Long Island City, N. Y.

Obituary

Samuel Insull (A'86, M'12, F'12) retired chairman of the board of the Commonwealth Edison Company, Chicago, Ill., died July 15, 1938. Doctor Insull was born November 11, 1859, in London, England, and was educated in private schools in London and later at Reading and Oxford. He received the degree of doctor of science from Union College in 1917 and the degree of doctor of laws from Northwestern University (1926), Notre Dame University (1926), and Queen's University (Canada, 1930). In 1881 he came to the United States, becoming private secretary to Thomas A. Edison, of whose business affairs he had charge for many years. Doctor Insull represented the Edison interests in the organization and management of The Electric Tube Company, Edison Machine Works, and Edison Lamp Company. He was the first general manager of the Edison Machine Works, and in 1889, when the various Edison manufacturing organizations were consolidated into the Edison General Electric Company, he was appointed second vice-president in charge of manufacturing and sales. When the Edison General Electric Company was merged with the Thomson-Houston Company to form the General Electric Company in 1892, Doctor Insull became second vice-president of the new company. He resigned in the same year, however, to become president of the Chicago Edison Company and the Consolidated Electric Company. In 1907 the two companies were merged to form the Consolidated Edison Company, with Doctor Insull as president. He became chairman of the board in 1930, and was an officer or director of many other public utility companies until his retirement in 1932.

Sir John Francis Cleverton Snell (A'06, M'06, F'12) former chairman of His Majesty's Electricity Commissioners, London, England, died July 6, 1938. Sir John was born December 15, 1869, at Saltash, Cornwall, and was educated at King's College in London. For three years he was assistant engineer for Crompton and Company, in which position he became engaged in central-station work in both England and Sweden. He then became chief assistant to a consulting engineer for three years before being appointed resident engineer for the Borough Council in London. Sir John was Borough Electrical and Tramways Engineer to the Sunderland Corporation for 9½ years before becoming a partner in the firm of Preece, Cardew, and Snell in 1906. He continued in private consulting work until 1918. He was knighted in 1914, and during 1914–15 was president of the Institution of Electrical Engineers. From 1926 until 1931 he was a vice-president of the Institution of Civil Engineers. At various times Sir John was a member of the British Advisory Council for Scientific and Industrial Research, chairman of the Water Power Resources Committee, and chairman of the Committee on Electroculture of the Ministry of Agriculture. He retired as chairman of the Electricity Commission at the end of 1937. Sir John was the Faraday Medalist of the Institution of Electrical Engineers in 1938.

Thomas Ahearn (A'87, M'87) president of the Ottawa Electric Company, Ottawa Electric Railway Company, Ottawa Car Manufacturing Company, and Ahearn and Soper, Ltd., Ottawa, Ont., Canada died June 28, 1938. Mr. Ahearn was born in Ottawa, June 24, 1855, and began his career as a telegraph operator in 1870. Later he

pioneered in the telephone field in Ottawa, taking charge of the telephone branch of the Montreal Telegraph Company in 1878. In 1883 Mr. Ahearn became a partner in the firm of Ahearn and Soper, an electrical contracting organization which later planned and founded many electrical companies. He was a founder in 1887 of the Chaudiere Electric Light and Power Company, merged in the Ottawa Electric Company in 1893, and, with the Ottawa Gas Company, absorbed by the Ottawa Light, Heat, and Power Company. He was also a founder of the Ottawa Electric Railway Company. In 1928 he was rewarded for his enterprise in business and industry by appointment to the Privy Council. Mr. Ahearn served as a director of the Bell Telephone Company of Canada, the Canadian Westinghouse Company, Ltd., the Northern Electric Company, and various other organizations.

Andrew James Cunningham (A'35, M'36) electrical traction engineer for the Metropolitan-Vickers Electrical Company, Ltd., Manchester, England, died in December 1937, according to word just received at Institute headquarters. Mr. Cunningham was born November 19, 1892, at Edinburgh, Scotland, attended Emmanuel College and Battersea Polytechnic, and was graduated in electrical engineering from the City and Guilds Institute of London, in 1916. From 1915 until 1918 he was associated with Buller, Ltd., London, and from 1918 until 1922 was electrical and civil engineer for the Twiss Electric Transmission Company, London. He held a similar position with Merz and McLellan, London, from 1922 until 1933. He became affiliated with the Metropolitan-Vickers Company in 1933, and represented that company in the design and construction of electrified railway systems on five continents.

Charles Norman Brubaker (A'19, M'29) manufacturing engineer of the power transformer department, General Electric Company, Pittsfield, Mass., died May 3, 1938. Mr. Brubaker was born at Liverpool, Pa., February 2, 1886, and was graduated from Bucknell University in 1911. Following his graduation he entered the General Electric Company's test course at Schenectady, N. Y. Upon completion of his duties in the test course, Mr. Brubaker served as a designing engineer before being transferred to Fort Wayne, Ind., in 1920. Six years later he moved to the Erie (Pa.) works of the General Electric Company, where he was appointed managing engineer of the transformer section. He became manufacturing engineer in the power transformer department at Pittsfield in 1932.

Burt J. Denman (A'11) vice-president and general manager of the United Light and Power Company, Chicago, Ill., died June 25, 1938. Mr. Denman was born April 30, 1876, at Toledo, Ohio, and was graduated from the University of Michigan in 1899 with the degree of bachelor of science in electrical engineering. Following his graduation he served for two years as instructor at Toledo University, following which he became electrical engineer for the Toledo, Bowling Green, and Southern Traction Company, remaining with that company until 1904, when he became an engineer for The Detroit Edison Company. He became vice-president and general manager of the United Light and Power Company and the United Light and Railway Company in 1913.

Richard J. Knaur (A'22) died April 26, 1938. Mr. Knaur was born January 17, 1870, at Maehrisch Ostrau, Austria, and attended the Technical University of Vienna. Early in his career Mr. Knaur took the student test course of the General Electric Company, Schenectady, N. Y., then went to Vienna to work for Siemens and Halske. In 1904 he became technical manager of Felten and Guilleaume, Vienna. He kept that position until 1922, when he was appointed general manager. In 1936, after 31 years of active service with Felten and Guilleaume, he resigned his position as general manager and was elected member and chairman of the board.

Dinshaw Pestonji Munshi (A'32), chief mechanical and electrical engineer for the Burhanpur Taft Mills, Ltd., Burhanpur, India, died December 16, 1937, according to word just received at Institute headquarters. Mr. Munshi was born June 6, 1882, at Naresari, India and was graduated from the Technological Institute of Great Britain in 1929. In 1900 he was employed by the New Great Eastern Spinning and Weaving Mills, Ltd., remaining there for seven years before becoming associated with the Lakhshmi Cotton Mills, Ltd., Sholapur, India. He entered the employ of the Burhanpur Taft Mills, Ltd., in 1920.

Algy Ross Battern (A'20) assistant general manager of the Iowa Public Service Company, Sioux City, died recently. Mr. Battern was born November 13, 1890, at Storm Lake, Iowa, and attended Highland Park College (Des Moines, Iowa). From 1910 until 1915 he was employed by the Storm Lake Electric Light and Power Company, Storm Lake, Iowa, in the latter year becoming a meterman for the Iowa Light, Heat, and Power Company at Storm Lake. Eventually he became engineer, and remained with that company until 1928, when he became affiliated with the Iowa Public Service Company.

Edson F. Packer, Jr. (A'36) draftsman for the Electric Service Supplies Company, Philadelphia, Pa., died June 13, 1938. Mr. Packer was born February 18, 1913, at Philadelphia, and was graduated from Drexel Institute with the degree of bachelor of science in electrical engineering in 1935. Following his graduation he entered the employ of the Electric Service Supplies Company and had served for three years as a draftsman.

Membership

Recommended for Transfer

The board of examiners, at its meeting on July 21, 1938, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

DuVall, W. C., professor of electrical engineering, University of Colorado, Boulder.
Stanbury, Carroll, development engineer, Cutler-Hammer, Inc., Milwaukee, Wis.
Stevens, Theodore, consulting engineer, Herne Bay, England.
Scott-Taggart, John, consulting engineer, Harlow Laboratories, Frinton-on-Sea, England.

4 to Grade of Fellow

To Grade of Member

Battey, P. L., senior partner, Battey and Childs, Chicago, Ill.
Book, C. F., meter engineer, Hydroelectric Power Commission of Ontario, Niagara Falls, Ont., Canada.
Bower, M. M., transmission engineer, Bell Telephone Laboratories, Inc., New York, N. Y.
Breon, K. H., power engineer, Pennsylvania Power and Light Company, Williamsport, Pa.
Burlingame, R. E., electrical and radio engineer and patent attorney, Williamson and Williamson, Minneapolis, Minn.
Comstock, C. W., consulting engineer, Jackson Heights, N. Y.
Helwig, W. O., secretary, Helwig Company, Milwaukee, Wis.
Kingdon, H. P., works manager, Commonwealth Electric Corporation, Ltd., Welland, Ont., Canada.
Knaus, Fred, senior contract agent, lighting department, city of Seattle, Wash.
Lawrence, W. T., eastern district engineer, Automatic Electric Company, New York, N. Y.
Lehman, C. D., engineer, The National Board of Fire Underwriters, Chicago, Ill.
Miller, J. F., assistant superintendent, Louisville Gas and Electric Company, Louisville, Ky.
Moench, H. A., assistant professor of electrical engineering, Rose Polytechnic Institute, Terre Haute, Ind.
Osborne, I. H., electrical engineering, Federal Shipbuilding and Dry Dock Company, East Orange, N. J.
Roberts, L. C., engineer, Bell Telephone Laboratories, Inc., New York, N. Y.
Smith, C. E., assistant chief engineer, Radio Stations WHK-WCLE, Cleveland, Ohio.
Smith, M. T., engineer, General Radio Company, Hollywood, Calif.
Sutton, L. V., president, general manager, and director, Carolina Power and Light Company, Raleigh, N. C.

18 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before August 31, 1938, or October 31, 1938, if the applicant resides outside of the United States or Canada.

United States and Canada

Almond, E. P. (Member), Tennessee Valley Authority, Knoxville, Tenn.
Biggs, R. N., City Hall, Petersburg, Va.
Blum, L. M., 1844 Clay Avenue, Bronx, New York, N. Y.
Chadwick, W. L. (Member), Southern California Edison Company, Los Angeles, Calif.
Chaney, J. G., Texas Agricultural and Mechanical College, College Station.
Doll, E. B., University of Kentucky, Lexington.
Edie, L. C., Western Union Telegraph Company, Dallas, Texas.

Ellsworth, B. E. S., Iowa-Nebraska Light and Power Company, Lincoln, Nebr.
Hawksley, R. W., Columbia Steel Company, San Francisco, Calif.
Hoff, O. C., The Pacific Telephone and Telegraph Company, Portland, Ore.
Howe, E. B., Potomac Electric Power Company, Washington, D. C.
Keller, W. J., Sr., 203 Natchez Building, New Orleans, La.
King, D., The Shawinigan Water and Power Company, Montreal, Que., Canada.
Mahler, R. J., Central Hudson Gas and Electric Corporation, Poughkeepsie, N. Y.
Marny, R. G., Hotel New Yorker, New York, N. Y.
Masters, D. B., Commonwealth and Southern Corporation, Jackson, Mich.
Nodder, W. R., Pacific Electric Manufacturing Corporation, San Francisco, Calif.
Redeker, I. M., Stanford University, Stanford University, Calif.
Wallin, M. R. (Member), Union Electric Company of Missouri, St. Louis.
Wallio, M. A., General Electric Company, Pittsfield, Mass.
Williams, J. W. A., International Power and Paper Company, Deer Lake, Newfoundland.

Total, United States and Canada—21

Elsewhere

Beadman, C. B. H. (Member), Callender's Cable and Construction Company, Ltd., Bombay, India.
De Lima, S. J., Power House, Bangalore Cantonment, India.
Doetsch, J. A., Neptun Gold Mining Company, Puerto Cabezas, Nicaragua.

Total, elsewhere—3

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Ackerson, Cornelius, 2600 West Grand Boulevard, Detroit, Mich.
De Lay, R. E., 77 Prospect Ave., Long Beach, Calif.
Fetter, Charles H., Electrical Research Products, 250 W. 57th St., New York, N. Y.
Kapell, Sidney M., 3043 Emmons Ave., Brooklyn, N. Y.
Lynch, Earl M., 34–40 West Beaver Street, Jacksonville, Fla.
Markham, Thomas C., Jr., 55 Hanson Place, Brooklyn, N. Y.
Neiman, William E., 4060 Elbertson Street, Elmhurst, N. Y.
Nissar, A. R., in care of Thomas Cook and Son, 2 Place de la Madeleine, Paris, France.
Piltch, Abraham, 2224 Eutaw Place, Baltimore, Md.
Platterer, Alvin, 776 N. Cass St., Milwaukee, Wis.
Powers, Walter H., 603 West Washington, Jackson, Mich.
Renking, H. L., 208 N. Broadway, St. Louis, Mo.
Robison, R. L., 941 E. Northlake Ave., Seattle, Wash.
Skina, Fred A., 626 Ash St., Moscow, Idaho.
Whitney, T. G., Electrical Research Products, Inc., 250 W. 57th St., New York, N. Y.
Willick, Francis L., 2397 East Grand Boulevard, Detroit, Mich.

16 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Society Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

BOTH SIDES of the MICROPHONE, Training for the Radio. By J. S. Hayes and H. J. Gardner. Philadelphia and New York, J. B. Lippincott Company, 1938. 180 pages, 8 by 5 inches, cloth, $1.25. Discusses the phases of broadcasting which are concerned with programs, sales, publicity, engineering, production, and announcing.

(The) AMERICAN YEAR BOOK, edited by W. M. Schuyler and A. B. Hart. New York, N. Y., Thomas Nelson and Sons, 1938. 993 pages, tables, 8 by 5 inches, cloth, $7.50. A survey of events during the year 1937 in 27 major fields of activity. Economics, business and science are adequately represented, with surveys of the mineral industries, manufactures, transportation, engineering, and construction.

DUODECIMAL ARITHMETIC. By G. S. Terry. New York and Longon, Longmans, Green and Company, 1938. 300 pages, charts, tables, 12 by 10 inches, cloth, $7.50. The number 12 as a base for our number system is strongly advocated in this publication. The author demonstrates the advantages of this system as compared with the base often in various mathematical operations from simple multiplication to the manipulation of the higher mathematical functions.

ELECTRON OPTICS in TELEVISION. By I. G. Maloff and D. W. Epstein. New York and London, McGraw-Hill Book Company, 1938. 209 pages, illustrated, 9 by 6 inches, cloth, $3.50. Develops the theory of electron optics and its most useful application, the television cathode-ray tube. An introduction briefly describes a complete cathode-ray television system and a few applications of electron optics. Following a discussion of electron emission and electron optics, part two discusses the television cathode-ray tube.

ELEKTRISCHE GASENTLADUNGSLAMPEN. By W. Uyterhoeven. Berlin, Julius Springer, 1938. 364 pages, illustrated, 9 by 6 inches, cloth, 36.40 rm.; paper, 34 rm. Theoretical and practical information concerning electric vapor lamps, including electronic and atom theory and the kinetic theory of gases and gaseous discharges. A section on the design of neon, sodium, and low- and high-pressure mercury-vapor lamps is included.

(The) EVOLUTION of PHYSICS. By A. Einstein and L. Infeld. New York, Simon and Schuster, 1938. 319 pages, illustrated, 8 by 6 inches, cloth, $2.50. Intended for the layman without any concrete knowledge of physics and mathematics; is clear and straightforward in style, and authoritative.

MUNICIPAL YEAR BOOK, 1938. Edited by C. E. Ridley and O. F. Nolting. Chicago, International City Managers' Association, 1938. 619 pages, illustrated, 10 by 7 inches, cloth, $5.00. An annual résumé of activities and statistical data of American cities.

PIEZOELEKTRIZITÄT des QUARZES. (Wissenschaftliche Forschungsberichte Naturwissenschaftliche Reihe, Bd. 45.) By A. Scheibe. Dresden and Leipzig, Verlag von Theodor Steinkopff, 1938. 233 pages, illustrated, 9 by 6 inches, paper, 20 rm.; bound, 21 rm. The widely scattered literature on the piezoelectric properties of quartz crystals and their practical applications presented in a review.

REPORTS on PROGRESS in PHYSICS, volume 4, edited by A. Ferguson. Cambridge, England, University Press; London, Physical Society, 1938. 389 pages, illustrated, 10 by 7 inches, leather, $5.00. Issued under the auspices of the Physical Society as an annual survey of advances in physical science. The present volume is as of the end of 1936; includes reviews of the work in heat, spectroscopy, sound, experimental electricity and magnetism, the charge of the electron, atomic physics, and other subjects of interest to electrical engineers.

SEVENTY YEARS of the WORCESTER POLYTECHNIC INSTITUTE. By H. F. Taylor. Worcester, Mass., Worcester Polytechnic Institute, 1937. 415 pages, illustrated, 9 by 6 inches, cloth, $2.00. An account of the founding and development of the Worcester Polytechnic Institute, containing information concerning persons, policies, activities, courses of instruction, and other matters.

TEXT-BOOK of CONVERGENCE. By W. L. Ferrar. Oxford, England, Clarendon Press; New York, Oxford University Press, 1938. 192 pages, diagrams, tables, 9 by 6 inches, cloth, $3.50. A mathematical treatise on convergence, presenting such information necessary for a university course in pure and applied mathematics.

ELEMENTS of THERMODYNAMICS. By E. M. Fernald. Second edition, New York and London, McGraw-Hill Book Company, 1938. 330 pages, diagrams, charts, tables, 9 by 6 inches, cloth, $3.50. A textbook presenting the subject with special reference to its applications in engineering. Includes the customary topics of general phases and states, steam cycles, refrigeration cycles, gas mixtures, compressed air, flow phenomena, combustion, and available energy.

RADIO-FREQUENCY ELECTRICAL MEASUREMENTS. By H. A. Brown. Second edition New York, McGraw-Hill Book Company, 1938. 384 pages diagrams, charts, tables, 9 by 6 inches, cloth, $4.00. A guide for radio-engineering laboratory instruction. Within each chapter, covering a particular group of measurements of circuit constants, frequency, electron-tube coefficients, etc., the principles are explained, the laboratory equipment and procedure are described, and the precision attainable, the necessary precautions and the merits of the methods are discussed.

NATIONAL PHYSICAL LABORATORY REPORT for the YEAR 1937. London, His Majesty's Stationery Office, 1938, 150 pages, tables, 10 by 6 inches, paper, 2s. 6d. (obtainable from British Library of Information, 270 Madison Avenue, New York, N. Y., $0.80). Presents the reports of the naval laboratory and the departments of physics, electricity, radio, metrology, engineering, metallurgy, and aerodynamics, indicating the state of the current researches.

(A) MODERN SPANISH-ENGLISH and ENGLISH-SPANISH TECHNICAL and ENGINEERING DICTIONARY. By R. L. Guinle. New York, E. P. Dutton and Company, 1938. 311 pages, 10 by 6 inches, cloth, $4.00. There are relatively few dictionaries of Spanish and English technical terms. This is the work of an English engineer with long experience in South America. The vocabulary covers the terms used in civil, mechanical, and electrical engineering.

KORROSIONEN an BISEN und NICHTEISENMETALLEN. By A. Siegel. Berlin, J. Springer, 1938. 86 pages, illustrated, 11 by 8 inches, cloth, 21.60 rm.; paper, 19.50 rm. discusses the phenomenon of the pitting of iron and nonferrous metals, and is based upon experience in electric power plants and on ships.

ISAAC NEWTON, 1642–1727. By J. W. N. Sullivan, with a memoir of the author by C. Singer. New York, Macmillan Company, 1938. 275 pages, 9 by 6 inches, cloth, $2.50. A new biography in which the purpose has been to paint a clear picture of Newton, the man, stressing the events which influenced his career and throw light on his character. Discusses his scientific achievements particularly in their relation to the contemporary scene and subsequent developments.

ENGINEERING ELECTRONICS. By D. G. Fink. New York and London, McGraw-Hill Book Company, 1938. 358 pages, illustrated, 6 by 9 inches, leather, $3.50. A practical volume for engineers who wish to take up or review electronic principles and their application in typical engineering problems of tube use and circuit design. Covers the fundamentals of electron physics and electron tube structures, the engineering characteristics of a wide variety of tubes, and a demonstration of the application of tubes in a variety of electrical and industrial problems.

(The) J. & P. TRANSFORMER BOOK. By S. A. Stigant and H. M. Lacey. Seventh edition. London, Johnson & Phillips, Ltd., 1937. 916 pages, illustrated, 9 by 6 inches, cloth, 12s. 6d., plus 9d. postage in the British Isles or 12s. 6d. plus postage to any other destination. Previous item (*EE, June '38, p. 276*) erroneously quoted price of seventh edition at 6s. 6d.

Engineering Societies Library

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MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

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Papers Presented at Winter Convention, New York, N. Y., January 24–28, 1938

No.	Authors	Titles of Papers (Some Shortened)
☐ 37-91	Aiken & Birdsall	*Sharp Cut-Off in Vacuum Tubes, Slide-Back Voltmeter
☐ 37-100	Hardaway & Lewis	*Test and Operation of Petersen Coil on 100-Kv System
☐ 37-101	Woodruff	*Transmission-Line Transients in Motion Pictures
☐ 37-112	Sporn and Muller	*The Application and Performance of Carrier-Current Relaying
☐ 37-114	Kierstead	*Some Schemes of Current-Limiting Reactor Applications
☐ 37-115	McEachron & McMorris	*Discharge Currents in Distribution Arresters—Part II
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* These papers have been published in the TRANSACTIONS section of ELECTRICAL ENGINEERING
†These papers to be published in TRANSACTIONS section of September issue.

Transactions

Papers and Discussions Comprising Pages 423–92 of the 1938 Volume

Subharmonics in Circuits Containing Iron-Cored Reactors

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Synopsis: The performance of a series circuit consisting of a resistor, a capacitor, an iron-cored inductor, and a sinusoidal impressed voltage is specified by the non linear differential equation

$$\frac{d\psi}{dt} + ri + L\frac{di}{dt} + \frac{1}{C}\int i\,dt = E\sin(t+\theta)$$

in which ψ is an odd function of i. Particular solutions of this equation, showing the effect of varying boundary conditions, are obtained by means of the differential analyzer. An approximate analytical method for determining the types of oscillations possible in this circuit is developed. Results obtained by this method are compared with differential analyzer solutions.

Introduction

THE BEHAVIOR of circuits involving iron-cored inductors, which saturate so that their reactances cannot be considered constant, has been studied for many years. Bethenod[1] in 1907 and Martienssen[2] in 1910 both noted that in such circuits more than one sustained value of current could be obtained for the same value of applied voltage and the same circuit parameters. The current obtained in a given case was found to depend on the way in which the phenomenon was initiated. In 1926, Mauduit[6] obtained oscillograms in which the principle component of current had a frequency which was a submultiple of the frequency of the applied voltage. Such a component of current will be referred to as a *subharmonic*. Mauduit's circuit was studied more completely by Fallou,[7] who suggested that such an arrangement could actually be used as a frequency divider.

Pederson,[8] who has made a very thorough study of subharmonics in linear circuits in which the parameters vary periodically with time, also mentions the possibility of obtaining subharmonics when the inductance varies with the current.

Recently, the increasing use of series capacitors to overcome the inductive drop in transmission systems has revived interest in subharmonic oscillations. In this case it is desirable to know the range of circuit parameters for which these subharmonic oscillations can exist, and the kinds of shock excitation which may initiate them, so that they can be avoided in the engineering of series capacitor installations. This aspect of the problem was treated in some detail in a recent paper by J. W. Butler and Charles Concordia.[26]

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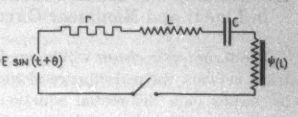
1. For all numbered references, see list at end of paper.

I. Statement of the Idealized Problem

This paper is limited to considerations of the simplest known circuit which exhibits the phenomenon. This is a series circuit consisting of a constant resistance, a constant inductance, a constant capacitance, and an inductor which varies due to magnetic saturation of its core. A sine wave voltage of unvarying maximum value is impressed. This circuit is shown in figure 1.

Figure 1. Idealized circuit



The following idealizing assumptions regarding the inductor will be made:

1. The winding resistance and distributed capacitance are equal to zero.
2. All hysteresis effects in the inductor may be neglected. Hence the saturation curve is a single-valued function.
3. There are no eddy currents in the core.

Any resistance actually present in the inductor may be lumped with the external resistance. Consistent with these assumptions the voltage across the reactor may be expressed as:

$$e = \frac{d\psi}{dt}$$

where ψ is the flux linkages of the inductor. The flux linkages and the current through the inductor are related in the way expressed by the familiar B-H curve of a circuit containing iron. Since this relationship is an odd function, the current may be expressed by the series

$$i = a_1\psi + a_3\psi^3 + \ldots + a_{2m-1}\psi^{2m-1} + \ldots \qquad (1)$$

The equation of the circuit is

$$ri + L\frac{di}{dt} + \frac{1}{C}\int i\,dt + \frac{d\psi}{dt} = E\sin(t+\theta)^* \qquad (2)$$

* The treatment in this paper is entirely mathematical; the symbols r, L, i etc., may be regarded as representing the physical quantities in any consistent unit system including per-unit.

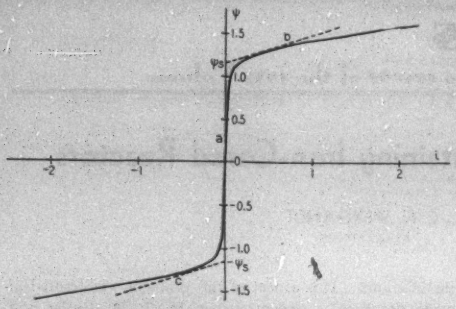


Figure 2. Experimental saturation curve and the straight-line approximation used in this paper

The problem is to determine under what conditions sustained currents of frequency lower than the impressed frequency can exist and to calculate the values of such currents.

II. The Effect of Initial Conditions in Linear and Nonlinear Circuits

The term *linear circuit* will be used to describe an electrical network the performance of which may be specified by means of a differential equation having coefficients which are not functions of the dependent variable, i.e., the coefficients are constants or functions of time only.

The term *nonlinear circuit* will be used to describe any circuit to which these conditions do not apply.

Equation 2 evidently may be transformed into a differential equation of the second order. Since ψ contains i to powers other than the first, the equation is *nonlinear*. It can be proved by application of the Lipschitz[25] condition that there exists one and only one solution of this equation corresponding to a given set of initial conditions.

Before considering the solution of the nonlinear equation let us recall the nature of the solution of a similar *linear* differential equation with constant coefficients. Here it is well known that the solution corresponding to any set of initial conditions is unique. The solution consists of two parts, a complementary function and a particular integral. In the case of a second-order equation, the complementary function contains two constants which depend upon the initial conditions whereas the particular integral is independent of the initial conditions. In equations representing practical electric circuits the complementary function dies out as time goes on, so that after sufficient time has elapsed the solution of the equation, for all practical purposes, is given by the particular integral alone. Therefore, in a circuit having constant parameters, the current which flows after a time long compared with the time constant of the circuit is independent of the initial conditions. This current is ordinarily called the *steady-state* current. That part of the current which becomes sensibly zero after a sufficient interval of time, is called the *transient* current. The division of the total current into *steady-state* and *transient* components is possible mathematically by virtue of the property peculiar to linear differential equations known as superposition.

In nonlinear equations this principle of superposition does not hold; the solution for any value of the independent variable, however large, will in general depend upon the initial conditions. Physically, this means that the current which flows in a nonlinear circuit a week after the switch was closed may depend on the phase angle of the impressed voltage at the instant of closing the switch. An example of this, in a special case where an analytical solution is possible, is given below. In many physical systems the solution after a relatively short interval of time has elapsed is periodic. It is therefore possible, by extrapolating this periodic solution back to the instant at which the phenomenon was initated, to split the solution into two parts, the periodic part which may be called a *steady state*, plus a part which dies out rapidly with time and hence might appropriately be called a *transient*.

Neither of these separate parts can be derived independently from the differential equation and the specified boundary conditions, as is possible with linear circuits. Furthermore, there is no reason to expect the periodic part to be independent of the initial conditions. This revision of the usual concept of "steady state" and "transient" is necessary if the terms are to be applied to currents which flow in nonlinear circuits.

Example Showing the Effect of Initial Conditions

Consider equation 2 in the special case when $E = 1$; $r = 0$; $\psi = Ki^{1/3}$:

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt + K\frac{d(i^{1/3})}{dt} = \sin(t+\theta) \tag{3}$$

Now let us assume the solution

$$i_a = A^3\cos^3\frac{t+\theta}{3} = \frac{A^3}{4}\left[3\cos\frac{t+\theta}{3} + \cos(t+\theta)\right] \tag{4}$$

where A is an undetermined coefficient.

Substituting the value i_a from (4) in (3) and equating coefficients of sines and cosines of like multiples of $(t+\theta)$ the following relationships can be derived:

$$K = \frac{3}{4}A^3\left[\frac{9}{C} - L\right]$$

$$4 = A^3\left[\frac{1}{C} - L\right] \tag{5}$$

Now let us assume another solution:

$$i_b = B^3\cos^3(t+\theta) = \frac{B^3}{4}\left[3\cos(t+\theta) + \cos 3(t+\theta)\right] \tag{6}$$

In the same way this gives rise to the relationships:

$$1 + KB = \frac{3}{4}B^3\left[\frac{1}{C} - L\right]$$

$$3L = \frac{1}{3C} \tag{7}$$

Any set of values of the parameters L, C, and K, which satisfies both the relationships (5) and (7) will form an equation having at least two solutions of the forms (4) and (6).

Such a set of values is:

$$L = 0.1$$

$$\frac{1}{C} = 0.9$$

$$K = 17.5$$

Equation 3 then becomes:

$$0.1\frac{di}{dt} + 0.9\int i\,dt + 17.5\frac{d(i^{1/3})}{dt} = \sin(t+\theta) \tag{8}$$

The two solutions are:

$$i_a = [-1.39\cos(t+\theta) + 0.462\cos 3(t+\theta)] \times 10^{-4} \tag{9}$$

$$i_b = 3.75\cos\frac{t+\theta}{3} + 1.25\cos(t+\theta) \tag{10}$$

That these are both solutions may be readily verified by substituting them in (8). They are entirely different in character, as one contains a term of higher frequency than the applied voltage, and the other a term of lower frequency than the applied voltage.

If the origin of time is taken as the instant when the current is passing through zero, we have for (9) the boundary conditions:

$$\theta = \frac{3\pi}{2} \qquad i_0 = 0 \qquad q_0 = 0.000124$$

The corresponding boundary conditions for (10) are:

$$\theta = \frac{3\pi}{2} \qquad i_0 = 0 \qquad q_0 = -10.0$$

If the switch were closed at the instant at which the voltage is at a negative peak and with an initial charge of -10 on the capacitor, the solution is given by equation 10. If the switch were closed at the instant at which the voltage is at a negative peak and with an initial charge of -0.000124 on the capacitor, the solution is given by equation 9. In general, if there were any other initial charge on the capacitor, or if the switch were closed at any other instant of time, a still different solution might be expected.

III. Physical Mechanism of Subharmonic Production

The physical nature of the phenomenon of subharmonic production is readily visualized if we consider the behavior of the circuit during the first few cycles after closing the switch. For simplicity let resistance be neglected, and let the boundary conditions be those of equilibrium. Let the phase angle θ be taken equal to zero. If the flux linkages in any constant inductor are included in ψ, the term $L\frac{di}{dt}$ does not appear, hence we have:

$$\frac{d\psi}{dt} + \frac{1}{C}\int i\,dt = E\sin t \tag{11}$$

from which

$$\psi = -E\cos t - \frac{1}{C}\iint i\,dt^2 + K$$

and since for $t = 0$ we have $\psi = 0$ and $i = 0$ it follows that $K = E$, hence

$$\psi = E(1-\cos t) - \frac{1}{C}\iint i\,dt^2 \tag{12}$$

The magnetization curve representing ψ as a function of i will be taken as shown by the solid curve in figure 2. The value ψ_s is the flux linkages at the knee of the curve.

Since the current during operation on the unsaturated portion of the ψ versus i characteristic is negligible, no appreciable current flows until $\psi = \psi_s$. From the closing of the switch until $\psi = \psi_s$, the integral $\frac{1}{C}\int\int i\,dt^2$ is therefore negligible and ψ is given nearly enough by $\psi = E(1-\cos t)$. The end of the interval during which this holds is indicated in figure 3*B* by T_1. The value of T_1 is given by

$$T_1 = \cos^{-1}\left(\frac{E-\psi_s}{E}\right) \tag{13}$$

Above the saturated value ψ_s the saturation curve may, to a reasonable approximation, be represented by a straight line. Let L^* be the slope of this line and let λ be the time measured from the instant T_1. Then during the succeeding brief interval the differential equation

$$L\frac{di}{d\lambda} + \frac{1}{C}\int i\,d\lambda = E\sin(\lambda + T_1) \tag{14}$$

holds, subject to the boundary conditions:

$$\lambda = 0 \qquad i = 0 \qquad q = 0.$$

The general solution of equation 14 is:

$$i = \frac{CE}{LC-1}\sin\left(\lambda + T_1 - \frac{\pi}{2}\right) + A\cos\left(\frac{1}{\sqrt{LC}}\lambda + \phi\right) \tag{15}$$

For the purpose of this illustration it will be sufficient to restrict the solution to the case in which the negative sign is taken in equation 15. This corresponds to the physical case of $L > \frac{1}{C}$. Inserting boundary conditions in (15) we have

$$i = \frac{CE}{1-LC}\cos(\lambda + T_1) - \frac{1}{1-LC}\sqrt{\frac{C}{L}}\times \sqrt{LC(E-\psi_s)^2 + \psi_s(2E-\psi_s)}\times \cos\left[\frac{\lambda}{\sqrt{LC}} + \tan^{-1}\sqrt{\frac{\psi_s(2E-\psi_s)}{LC(E-\psi_s)^2}}\right] \tag{16}$$

This equation holds only until the flux linkages are reduced to the value ψ_s. At this time the current effectively stops and whatever charge has been accumulated on the capacitor is trapped there until the flux linkages again reach the value $= \psi_s$. During the interval from T_1 to the instant at which current stops flowing, the value of ψ is given by equation 12, in which the term $\frac{1}{C}\int\int i\,dt^2$

* Note that L as used in this section is the sum of the saturated inductance of the reactor plus the external linear inductance.

must be evaluated by substitution of the proper function for i. However, after the charge is trapped on the capacitor, this term becomes $\frac{Q}{C}t$. Hence the flux linkages are given by the expression

$$\psi = E(1 - \cos t) - \frac{Q}{C}t - \psi_a \qquad (17)$$

where ψ_a is the value of flux linkages corresponding to $\int\int i\,dt^2$ when current ceased to flow. It is evident that equation 17 represents an oscillatory flux linkage which has a negative component proportional to time. A value $-\psi_s$ will therefore be reached in a time which is short if Q is large and relatively long if Q is small. It is possible that Q may be so small that several cycles of the impressed frequency may have elapsed before another pulse of current occurs. *It is the trapping of charge on the capacitor which gives rise to subharmonic oscillations in circuits of this type.*

IV. Summary of Available Methods of Solution

Step-by-step methods such as that given in the preceding section are very laborious and give the solution only for the parameters and initial conditions for which they are carried out. Such methods, however, have the advantage of shedding some light on the physical nature of the phenomena which the equation describes.

The differential analyzer furnishes a very convenient method of solving equation 2. While analyzer solutions are subject to the same limitations as those obtained by the step-by-step method, in that each solution is good only for the parameters and initial conditions for which it is made, the labor of carrying out a solution is not great. Therefore, it is possible, by carrying out a large number of particular solutions, to generalize to a certain extent. A severe limitation of this method arises from the fact that the analyzer insists on giving the whole solution, including the transient, and refuses to produce a steady state until the transient has died out. In circuits in which the damping is slight, which unfortunately are those of greatest interest, this involves a considerable loss in time as well as a sacrifice in accuracy due to accumulated errors in runs of long duration.

The various other methods which have been applied to nonlinear circuits, Taylor's series expansion, isocline and other graphical methods, the analytical method of Kryloff, etc., do not seem to be of very great value in the solution of the present problem.

Recursion formulas for the boundary conditions which may produce subharmonics are developed in the appendix. This method is an extension of the method used by Boyajian[17] for calculation of this circuit when the initial conditions are such as to produce no subharmonics. The method suffers from the fact that a considerable idealization of the problem is necessary in order to carry out the mathematical details, but has the peculiar advantage, not found in other analyses of the problem, of expressing the possible steady states in terms of the circuit parameters without regard to the method of initiating the phenomenon. Although not applicable to all cases of subharmonic production, this scheme seems to be the most powerful yet developed in those cases where it applies. A combination of differential analyzer and recursion formula solutions, the differential analyzer to give the solution in the initial period and the recursion formula to give the solution after a considerable elapsed time, is perhaps the most revealing analysis possible at present.

In figure 3, a comparison of solutions by the differential analyzer, step-by-step calculations, and by the recursion formula method given in the appendix, is shown.

Figure 3*A* shows the current, applied voltage, flux linkages, and charge on the capacitor as obtained by the differential analyzer. In this case, the relation between ψ and i is that shown by the solid curve in figure 2. The other parameters are

$$E = 0.7 \qquad L = 0.197 \qquad C = 4.66$$

It will be noted that at time T_B all the quantities have substantially the same values as at the time T_A. Therefore, from the point T_B on, the curves will be a periodic repetition of the portion from T_A to T_B. The parts of the curves from the start to the point T_A contained *transient* portions of the solution in the sense in which the word is used in this paper. After point T_A, the solutions are *steady state* in the sense in which the term is used here.

The curves in figure 3*B* were obtained by the step-by-step method used in the preceding section to illustrate the physical nature of the phenomenon. For this calculation it was assumed that the resistance was negligible. The value of the flux linkages at the knee of the saturation curve was taken to be $\psi_s = 1.15$. The value of inductance used was the sum of the external inductance and the slope of the saturation curve above the knee; this value was taken as $0.197 + 0.303 = 0.500$. The three terms of equation 17 are shown by the dotted curves; the resultant flux linkages are shown by a solid curve. This method could be carried on indefinitely, or until at the end of some interval all the boundary conditions were found to be the same as at the end of some previous interval, in which case the remainder of the solution would of course be a repetition of the part between points of indentical boundary conditions.

In order to eliminate a prohibitive amount of piece-by-piece calculation to find repetitive boundary conditions (quite conceivably for certain circuits and initial conditions none might exist) the method worked out in the appendix is used for calculating the steady state. This yields the curves shown in figure 3*C*. The solution turns out to be a subharmonic oscillation designated in the appendix as the third kind. A comparison with the upper curves shows that the agreement with the analyzer solution is very good in spite of the idealizing assumptions made.

Appendix—Recursion Formulas for Steady State Subharmonics

In order to circumvent mathematical difficulties, resistance will be neglected in this analysis. Further it will be assumed that the

Figure 3

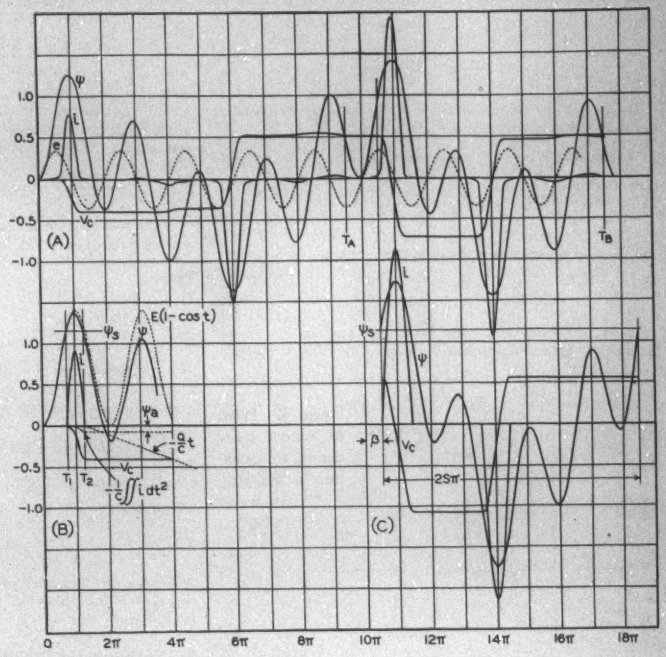
(*A*)—Differential-analyzer solution of the equation

$$\psi(s) = \int\left[0.7 \sin t - 0.05i - 0.197\frac{di}{dt} - 0.214\int i\,dt\right]dt$$

(*B*)—Approximate check of analyzer solution by step-by-step calculation

(*C*)—Approximate steady-state solution calculated from recursion relations

Scales:
Flux linkage is shown in per unit
Time is shown in radians of the impressed sinusoid
To obtain current in per unit multiply scale shown by 0.542
To obtain capacitor voltage in per unit multiply scale shown by 0.27
Maximum value of impressed voltage is 0.7 per unit



magnetization curve of the reactor may be represented by the dotted straight lines shown in figure 2. The curve consists of three portions labled in the figure *a*, *b*, and *c*. Curve *a* consists of the ψ axis between the values $-\psi_s$ and ψ_s. For curve *b* we have $\psi = Li + \psi_s$, $i > 0$. For curve *c* we have $\psi = Li - \psi_s$, $i < 0$.

I. Operation on Curve (a)

When operation is on the ψ axis the current is zero, hence the charge is constant. The flux linkages are given by the equation

$$\frac{d\psi}{dt} + \frac{Q_0}{C} = E \sin t \tag{18}$$

Integrating

$$\psi = -E \cos t - \frac{Q_0}{C}t + K \tag{19}$$

in which Q_0 is the charge trapped on the capacitor at the start of operation on (*a*). If at the start $t = T_0$ and $\psi = \psi_0$, we have

$$K = \psi_0 + E \cos T_0 + \frac{Q_0 T_0}{C} \tag{20}$$

The general expression for ψ during operation on (*a*), in terms of the boundary conditions for any given traverse of (*a*), is

$$\psi = -E \cos t - \frac{Q_0}{C}t + \psi_0 + E \cos T_0 + \frac{Q_0 T_0}{C} \tag{21}$$

II. Operation on Curve (b) or (c)

Assume that the capacitance has small effect in comparison with the inductance when operation is on either curve (*b*) or (*c*). Then

$$L\frac{di}{dt} = E \sin t \tag{22}$$

and

$$q = -\frac{E}{L}\sin t + At + B \tag{23}$$

Let the boundary conditions be taken as

$$t = T_k \qquad q = -Q_k \qquad i = 0 \tag{24}$$

then we have

$$A = \frac{E}{L}\cos T_k \tag{25}$$

and

$$B = -Q_k + \frac{E}{L}\sin T_k - \frac{ET_k}{L}\cos T_k \tag{26}$$

The general expressions for the charge and current during operation on (*b*) or (*c*), in terms of the boundary conditions for any given traverse of (*b*) or (*c*), are

$$i = \frac{E}{L}(\cos T_k - \cos t) \tag{27}$$

$$q = \frac{E}{L}(\sin T_k - \sin t - T_k \cos T_k + t \cos T_k) - Q_k \tag{28}$$

III. Time Interval and Change in Charge During One Excursion in the Saturated Region

It will be assumed that when i becomes zero, operation on the saturated portion of the characteristic ceases (in exceptional cases this

need not be true). Let T_{k+1} be the instant of time at which this occurs.

From (27)

$$\cos T_{k+1} = \cos T_k \tag{29}$$

The instant T_{k+1} occurs later than T_k, but not more than 2π later. It will be convenient to express T_k as

$$T_k = 2r\pi + \beta \qquad \text{where } -\pi < \beta < \pi \tag{30}$$

from which it follows that

$$\begin{aligned} T_{k+1} &= 2(r+1)\pi - \beta & \beta > 0 \\ &= 2r\pi - \beta & \beta < 0 \end{aligned}$$

and the time of excursion in the saturated region is

$$\begin{aligned} T_{k+1} - T_k &= 2(\pi - \beta) & \beta > 0 \\ &= -2\beta & \beta < 0 \end{aligned} \tag{31}$$

The current which flows in the saturated region and the interval for which it flows depend upon the value of β. This is shown in figure 4. The change in charge due to the current flowing during this interval may be calculated from (28):

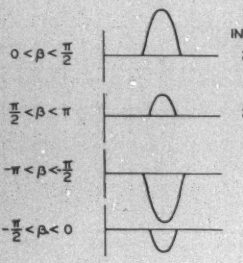


Figure 4. Types of current pulse during an excursion in the saturated region

$$\begin{aligned} Q_{k+1} &= \frac{2E}{L}[\sin\beta + (\pi - \beta)\cos\beta] - Q_k & \beta > 0 \\ &= \frac{2E}{L}[\sin\beta - \beta\cos\beta] - Q_k & \beta < 0 \end{aligned} \tag{32}$$

IV. Subharmonic Oscillation of the First Kind

One type of oscillation which may occur involves one excursion in the saturated region with positive current, one excursion down the ψ axis, one excursion in the saturated region with negative current and finally one excursion up the ψ axis to the beginning of a new cycle. Due to symmetry the charges must have the same magnitude but opposite signs in two successive excursions along the ψ axis. Such a cycle is indicated in figure 5 in which T_k has been chosen as the instant of time at which operation starts on the saturated portion of the characteristic with *positive* current. The angle β is therefore restricted to positive values.

The time interval for one complete cycle is equal to

$$T = 4(\pi - \beta) + 2\delta \qquad \beta > 0 \tag{33}$$

where δ is the time for one traverse of the ψ axis. Since for a subharmonic the period T must be given by

$$T = 2s_1\pi$$

we have

$$\delta = 2\beta + (s_1 - 2)\pi \qquad \beta > 0 \tag{34}$$

Further since the oscillation is assumed symmetrical, the angle of entrance into the negative saturated region must be an odd multiple of $\pi + \beta$. That is

$$\beta + 2(\pi - \beta) + \delta = \beta + (2n+1)\pi$$

where $n = 1, 2, 3, \ldots$. Comparing this expression with (34) it is seen that s_1 must be an odd integer. Oscillations of this kind are all *odd* subharmonics. Equation (32) gives the value of Q_k in terms of the angle β if we impose the condition $Q_{k+1} = Q_k$ (since $-Q_k$ was taken as the charge during travel up the ψ axis),

$$Q_k = \frac{E}{L}[\sin\beta + (\pi - \beta)\cos\beta] \tag{35}$$

If the boundary conditions corresponding to one travel up the ψ axis are inserted in (21) we have

$$\begin{aligned} \psi_0 &= -\psi_s & \psi &= \psi_s \\ Q_0 &= -Q_k & t &= 2r\pi + \beta \\ T_0 &= (2r - s_1 + 2)\pi - \beta & & \beta > 0 \end{aligned}$$

$$2\psi_s = E[\cos(\beta + s_1\pi) - \cos\beta] + \frac{Q_t}{C}[2\beta + (s_1 - 2)\pi] \tag{36}$$

Substituting (35) in (36), we have

$$\frac{2LC\psi_s}{E} = -2LC\cos\beta + [2\beta + (s_1 - 2)\pi][\sin\beta + (\pi - \beta)\cos\beta] \tag{37}$$

The alignment chart figure 6 gives solutions of this equation for various values of the parameters. In this chart

$$A = \frac{2LC\psi_s}{E} \qquad B = 2LC \qquad m = s_1 - 2$$

The dotted line in figure 6 gives a representative solution. In this case $A = 5.75$ and $B = 5$. For $m = 1$, we have two values of β, 10° and 102°. For $m = 3$, we have one value of β, 134°, etc.

V. Subharmonic Oscillation of the Second Kind

Another type of oscillation encountered experimentally is that shown in figure 7. This type corresponds to the route over the saturation curve outlined in the figure. In this case the charge $-Q_k$ which exists at the instant T_k, is removed due to the flow of current

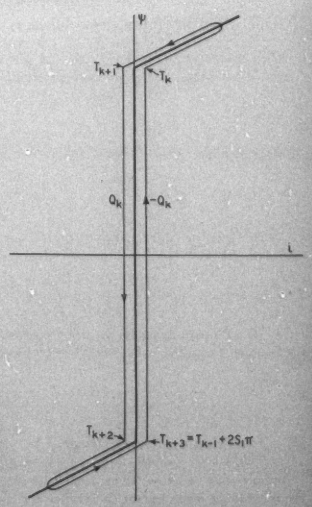


Figure 5. Path of subharmonic oscillation of the first kind

in the interval $(T_{k+1} - T_k)$, so that during the interval $(T_{k+2} - T_{k+1})$ the charge on the capacitor is zero. The value of the order s_2 of the subharmonic may be calculated as follows:

Half period $= (T_{k+4} - T_k) = (T_{k+4} - T_{k+3}) + (T_{k+3} - T_{k+2}) + (T_{k+2} - T_{k+1}) + (T_{k+1} - T_k)$

$$s_2\pi = 2\beta + (s_1 - 2)\pi + 2(\pi - \beta) + 2\beta + 2(\pi - \beta)$$

Hence s_2 is equal to $(s_1 + 2)$; s_2 is therefore an odd integer.

In the first type of oscillation the charge is reversed each time current flows; in the oscillation of the second kind the first pulse of current after an excursion along the ψ axis reduces the charge to zero and the second pulse charges the capacitor to a value equal and opposite to the original charge. Therefore equation 35 must be rewritten

$$Q_k = \frac{2E}{L}[\sin\beta + (\pi - \beta)\cos\beta] \tag{38}$$

Equation 36 remains unchanged. However we wish to express (36) in terms of s_2:

$$2\psi_2 = E[\cos(\beta + s_2\pi) - \cos\beta] + \frac{Q_k}{C}[2\beta + (s_2 - 4)\pi] \tag{39}$$

Substituting (38) in (39) we have:

$$\frac{LC\psi_2}{E} = -LC\cos\beta + [2\beta + (s_2 - 4)\pi][\sin\beta + (\pi - \beta)\cos\beta] \tag{40}$$

Solutions for various values of the parameters are given by the alignment chart figure 6. In this chart

$$A = \frac{LC\psi_2}{E} \qquad B = LC \qquad m = s_2 - 4$$

VI. Oscillation of the Third Kind

It sometimes happens, as in figure 3, that the condenser charge accumulated during the transient causes the two portions of a cycle to be unsymmetrical. As before let T_k be the instant of time at which operation starts on the positive saturated portion of the characteristic. The charge during the interval preceding T_k was $-Q_k$. During the interval $T_{k+1} - T_k$ the negative charge is removed and a *greater* positive charge Q_{k+1} is put on the condenser. Hence we have

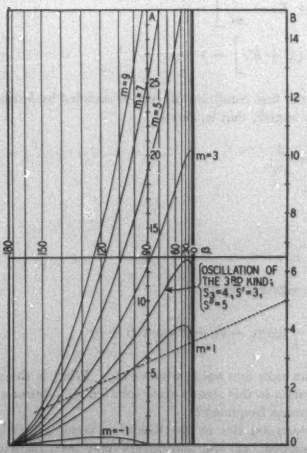
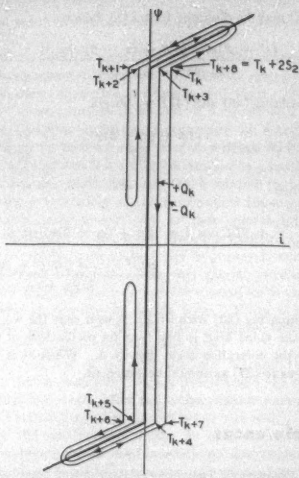


Figure 6. Alignment chart for the equation

$$A + B\cos\beta - (2\beta + m\pi)[\sin\beta + (\pi - \beta)\cos\beta] = 0$$

Figure 7. Path of subharmonic oscillation of the second kind



$$Q_k + Q_{k+1} = \frac{2E}{L}[\sin\beta + (\pi - \beta)\cos\beta] \tag{41}$$

If the two current pulses are to be the same, we have

$$T_{k+3} - T_k = \beta + s'\pi \qquad \text{where } s' \text{ is an odd integer} \tag{42}$$

and also

$$T_{k+4} - T_{k+3} = \beta + s''\pi \qquad \text{where } s'' \text{ is also an odd integer} \tag{43}$$

If $Q_{k+1} > Q_k$, as assumed, then s' which includes a passage along the ψ axis with charge Q_{k+1} will be smaller than s'' which includes a passage along the ψ axis with a charge of Q_k; we have

$$2(\pi - \beta) + \delta' = s'\pi$$
$$2(\pi - \beta) + \delta'' = s''\pi$$

where δ' and δ'' are the two time intervals on the ψ axis.

$$\delta' = 2\beta + (s' - 2)\pi \tag{44}$$

$$\delta'' = 2\beta + (s'' - 2)\pi \tag{45}$$

The flux linkage equations become

$$2\psi_2 = -2E\cos\beta + \frac{Q_k}{C}[2\beta + (s'' - 2)\pi] \tag{46}$$

$$2\psi_2 = -2E\cos\beta + \frac{Q_{k+1}}{C}[2\beta + (s' - 2)\pi] \tag{47}$$

If we let Δ be the unbalanced charge and Q be the charge which is reversed at each current pulse we have

$$Q_k = Q - \Delta$$
$$Q_{k+1} = Q + \Delta \tag{48}$$

Subtracting (46) from (47), it follows that

$$\Delta = \frac{(s'' - s')\pi Q}{2[2\beta + (s_2 - 2)\pi]} \tag{49}$$

in which $s_2 = \frac{s' + s''}{2}$ is the order of the subharmonic.

Q may be obtained from (41), hence

$$\Delta = \frac{(s'' - s')\pi E[\sin\beta + (\pi - \beta)\cos\beta]}{2L\,[2\beta + (s_3 - 2)\pi]} \tag{50}$$

Adding (46) and (47), we obtain

$$\psi_3 + E\cos\beta = \frac{[2\beta + (s_3 - 2)\pi]Q}{2C} + \frac{(s' - s'')\pi}{4C} \tag{51}$$

Hence

$$\frac{2LC\psi_3}{E} + 2LC\cos\beta = [2\beta + (s_3 - 2)\pi][\sin\beta + (\pi - \beta)\cos\beta] - \frac{\pi^2(s'' - s')^2\,[\sin\beta + (\pi - \beta)\cos\beta]}{8[2\beta + (s_3 - 2)\pi]} \tag{52}$$

Comparing (52) with (37) it is seen that the solution for oscillations of the third kind is like that for oscillations of the first kind except for the correction term due to Δ. When s'' is equal to s' (52) reduces to (37) as should be expected.

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Discussion

Ernst Weber (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): In explaining the production of subharmonics in circuits containing iron-cored inductors the authors employ, in addition to the differential-analyzer attack, two phases of theoretical attack. The more important and most interesting one is the region-by-region method, substituting three straight lines for the nonlinear characteristic of the iron-cored inductor. Particularly happy is the concept of the "trapped" charge on the condenser which is amply confirmed by the results obtained with the differential-analyzer.

Less convincing is the attempt to show by a direct analytical attack the effect of initial conditions upon the "steady state" response of the nonlinear circuit. The circuit analyzed consists of a capacitance C in series with a linear inductance L and a nonlinear inductance of flux linkages $\psi = Ki^{1/3}$, and having an applied voltage $1.\sin(t + \theta)$, the time measured in radians. The circuit is treated as nondissipative, that is, disregarding resistances and this feature invalidates most of the reasoning. In order to show that the analysis cannot be valid, let us apply the authors' reasoning to a linear circuit of the same type. Then the flux linkages ψ can be expressed as $\psi = K.L$ and, in differentiating, can be combined with the first term Ldi/dt so that one obtains

$$(L + K)\frac{di}{dt} + \frac{1}{C}\int i\,dt = \sin(t + \theta) \tag{1}$$

Assume now that the solution of (a) consists of an n'th harmonic current in addition to the current of impressed frequency,

$$i_a = A\cos(t + \theta) + B\cos n(t + \theta) \tag{2}$$

where A and B are undetermined coefficients. Substitution of (2) and equating coefficients of sines of like multiples of $(t + \theta)$ leads to the two conditions:

$$\left.\begin{aligned} B\cdot\left[n(L + K) - \frac{1}{nC}\right] &= 0 \\ A\cdot\left[\frac{1}{C} - (L + K)\right] &= 1 \end{aligned}\right\} \tag{3}$$

Obviously the first condition (3) can be satisfied by letting the term in brackets vanish, that is, choose

$$(L + K) = \frac{1}{n^2C} \tag{4}$$

giving

$$A = \frac{n^2C}{n^2 - 1}$$

so that the solution finally is

$$i_a = \frac{n^2C}{n^2 - 1}\cos(t + \theta) + B\cos n(t + \theta) \tag{5}$$

where B can take any value whatsoever. What is the meaning of two frequencies in this steady-state solution for a linear circuit with single impressed frequency?

The explanation lies in the following facts: (1) resistance has been disregarded; (2) the parameters have been chosen to satisfy the resonance condition (4) for the n'th harmonic, making this a proper frequency of the circuit; (3) in a nondissipative circuit zero voltage can produce a current of arbitrary magnitude if resonance

exists; (4) in a nondissipative circuit the application of any voltage initially different from zero will excite a steady a-c current of the proper frequency which can persist indefinitely.

Now, the authors follow in the case of their nonlinear circuit exactly the same procedure as outlined above for the linear circuit. Since they assume for the flux linkages the law $\psi = Ki^{1/3}$, the introduction of the third harmonic (sub- or super-) is natural. Their solution does, therefore, *not* give the steady-state term but includes an involuntary a-c steady transient term as well. The nonlinearity hides this fact, particularly since the amplitude of the harmonic must have a special value in order to be able to satisfy the nonlinear differential equation. The conclusion of the authors that there can exist entirely different characteristic responses to an applied a-c voltage for different switching angles is not justified. In fact, experience shows that the final steady state as seen in oscillograms is typically the same for various switching angles, though not necessarily of exactly the same form. Otherwise any practical use of the relay circuits based upon the critical features of the ferroresonant element would be incomprehensible.

I. A. Travis and C. N. Weygandt: Doctor Weber shows that in a linear circuit with an applied voltage there can exist two sustained sinusoidal components of current having different frequencies, if resistance be neglected. One of these components has the frequency of the applied voltage whereas the other has a frequency dependent on the inductance and capacitance in the circuit but *not* dependent in any way upon the initial conditions. The initial conditions determine the maximum value of this component but do not influence the frequency.

In the nonlinear circuit given in part II of the paper there can be many solutions involving many frequencies. Of these we give two, which happen to be readily expressible in trigonometric form. The essential thing is that these solutions show that in a circuit with a given capacitor and nonlinear inductor, components of current having entirely different frequencies may flow depending on the initial conditions. Thus equation 9 is a solution containing a fundamental and a third harmonic, while equation 10 is a solution for the same circuit containing a fundamental and a one-third harmonic. In a given single mesh linear circuit such as that described by Doctor Weber it is impossible to get more than one frequency in addition to that of the applied voltage and this frequency is never dependent upon the initial conditions. The only special attribute of the one-third power with reference to these two solutions is that they are the only two expressible in simple form. Many other solutions were actually obtained on the differential analyzer, which had frequencies in no way related to the number three.

The question as to whether or not the solutions (9) and (10) contain "involuntary steady transient" terms, which might die out if resistance were considered is one which the authors cannot answer. The whole question of stability of subharmonics is one with which the present investigation did not concern itself. It is, however, believed that circuits having resistance exist in which can flow currents of frequency dependent on the initial conditions, and which so far as oscillographic study is concerned have every right to the name steady state.

Recovery-Voltage Characteristics of Typical Transmission Systems and Relation to Protector-Tube Application

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Introduction

THE SUCCESSFUL operation of an arc-interrupting device requires that the insulation recovery-voltage characteristics of the device be higher than the recovery-voltage characteristics of the system. A broad understanding of the recovery-voltage problem from the application point of view, requires a knowledge of the effects caused by the range of systems, by the different types of faults and the different fault conditions encountered in practice. With this object in mind an investigation was undertaken to provide a general picture of the recovery-voltage characteristics of transmission systems.

In order to carry out this investigation consideration was given to the several possible modes of attack which include analytical, field-test, and a-c calculating-board methods. Analytical methods are of limited value for such a study because of the involved nature of the problem, the range of conditions, and number of cases which must be considered. Field tests, although providing results of value as benchmarks, are of restricted use because it is impractical by this means alone to study an adequate number of conditions with suitable range of system constants and fault conditions. Because of these limitations in analytical and field-test methods, this investigation has been carried out by the a-c calculating-board method, described by the authors in a recent paper.[1]

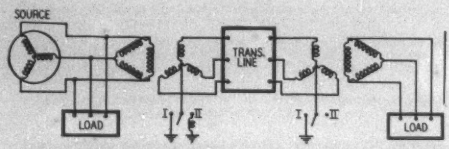

Figure 1. Schematic diagram of system selected for study

Group I—Solidly grounded at both ends. Used for curves of figure 6
Group II—Reactance grounded at sending end; ungrounded at receiving end. Used for curves of figure 7

It is proposed in this paper to present the results of general analyses made on a number of typical transmission systems subjected to faults of such a type that their clearing restores the systems to the original circuit conditions. This type of fault does not include the ordinary circuit-breaker sectionalizing operation but it does include the protector tube and many "shunt" type applications with circuit breakers or fuses whose operations do not change the main circuit condition. It is also proposed to illustrate the use of the results of such recovery-voltage studies with the application of protector tubes and to discuss the operating experience with certain typical applications. Although the usefulness of this general study will be illustrated by only one specific application the authors believe that it has a definite use in connection with other applications.

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1. For all numbered references, see list at end of paper.

Part I

Systems Selected for Analysis

A broad perspective of the recovery-voltage problem can be obtained from the study of a representative set of systems. For this purpose three-phase, 60-cycle systems with transmission lines of the three voltage classes, namely, 34.5, 69, and 138 kv were selected. Since the recovery voltage of a system is materially affected by the length of connected line, the lengths were selected to represent the shortest that would be encountered at that particular voltage for the large majority of systems. These selections were as follows: 22.5 miles for 34.5 kv, 45 miles for 69 kv, and 90 miles for 138 kv. Although it was recognized that more than one circuit would be required to transmit the maximum amount of power a single-circuit line was used because this gives the more severe recovery-voltage conditions.

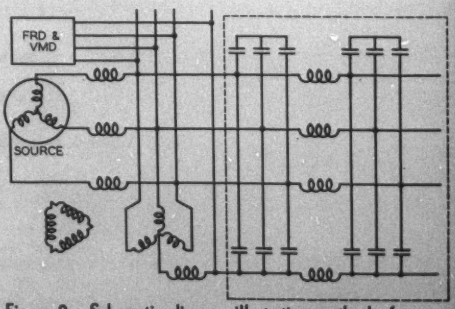

Figure 2. Schematic diagram illustrating method of system representation used on the a-c calculating board

FRD—Fault-representation device *VMD*—Voltage-measuring device

Table I. Characteristics of System Selected for Study

Voltage	34.5 Kv	69 Kv	138 Kv
Short-Circuit Amperes			
(a)	500	500	500
(b)	2,000	2,000	1,000
(c)	6,000	6,000	4,000
Short-Circuit Kva			
Load kva	5.0	4.0	3.0
Line length (miles)	22.5	45	90

The general features of these systems are shown schematically in figure 1. For each voltage class three different conditions were assumed, each having different values of generating capacity and load. Table I gives the symmetrical three-phase short-circuit current that would be encountered for a "bolted fault" at the sending end. Systems capable of supplying the higher short-circuit currents have in general larger connected loads. Table I gives the ratio of short circuit kilovolt-amperes to load kilovolt-amperes that was used in this study. Both no-load and loaded conditions were considered. An 80 per cent power factor load was divided equally between the generator bus and the receiver bus as shown in figure 1.

The generating and transformer capacities were proportioned to the load for the particular system and short-circuit current, and typical constants were assumed for all of the system elements. Transmission lines without ground wires were chosen. The additional complication to take care of the cases with ground wires is not warranted because the problems are similar and also the recovery voltages are less severe when ground wires are used.

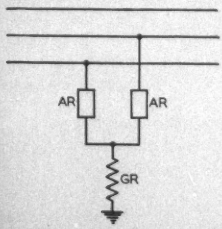

Figure 3. Connection diagram for double line-to-ground fault

AR—Arc-representation device
GR—Ground or tower-footing resistance

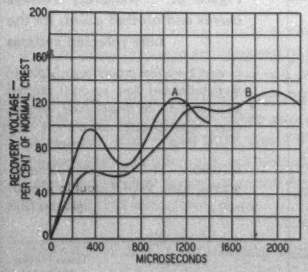

Figure 4. Examples of Cartesian plot of polar oscillograms taken during general studies

A—Single line-to-ground fault at sending end. 138-kv solidly grounded system having 1,000 amperes symmetrical three-phase short-circuit current, zero tower-footing and arc resistance, and load

B—Double line-to-ground fault at sending end. 138-kv solidly grounded system having 500 amperes symmetrical three-phase short-circuit current, 33.0 ohms tower-footing resistance, zero arc resistance, and load

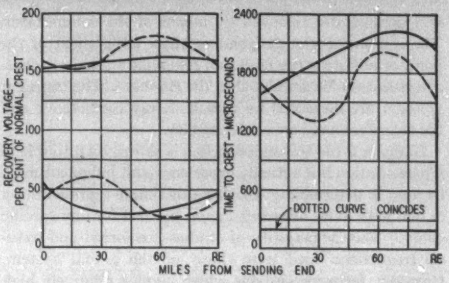

Figure 5. Recovery voltage for first and maximum crests and time to first and maximum crests as a function of location of fault on 90-mile solidly grounded 138-kv system supplying 826 amperes symmetrical three-phase short-circuit current at sending end

——— Single line-to-ground fault, no tower-footing or arc resistance
– – – – Double line-to-ground fault, 33.0 ohms tower-footing resistance

Variable Factors Considered in the A-C Board Study

In making the general analysis the factors that were varied were method of grounding, load, type of fault, fault resistance, arc resistance, and location of fault. The studies can conveniently be divided into two groups with respect to the method of grounding, namely: Group I with system solidly grounded both at sending- and receiving-end transformers, and group II with the system grounded through a reactance at the sending end only. The solidly grounded systems, of group I, were studied for both single line-to-ground and double line-to-ground faults and for fault or tower-footing resistance of 0, 25, and 100 ohms, and with and without resistance for arc representation. The effect of load was investigated by comparing the results of the above tests with results of a few tests made without load and without fault or arc resistance. The second set of tests for the reactance-grounded system, group II, was made with the addition of a neutral reactor of such magnitude as to make the zero-sequence reactance at the sending end equal to 8.5 or 34 times the zero-sequence reactance of the supply transformer.

Connection and Adjustment of the A-C Calculating Board

The method of connecting the a-c calculating board is illustrated in figure 2. The actual connection and adjustment of the board was similar to that described in the paper[1] referred to previously. The selected systems were set up in miniature on a three-phase basis and the fault

was applied and removed by means of the commutator. The commutator is designed to allow adjustment of the point of initiating the fault and removing it, and arc characteristics can be simulated in the circuits. The transient voltages are measured by a cathode-ray oscilloscope and the records secured on a rotating film.

In figure 2 the transmission line is shown by a simple pi representation but actually experience and judgment must be used in determining whether this simple representation or one with more branches should be used for any specific study. For the majority of studies the forced and natural frequencies used were those of the actual system. However, for some systems which involve relatively high natural frequencies it may be advantageous to use lower frequencies and apply proper corrections. The need for such a procedure depends upon the relative losses of the miniature and the actual systems. In this particular set of investigations it was necessary to use this procedure for the lower-voltage systems. Another network representation problem was encountered with systems having relatively low source inductance. In this case the transients had relatively large amounts of energy associated with the higher-frequency components and adjustments were required to compensate for the increased attenuation.

The general procedure of making adjustments and obtaining the recovery voltage has been described in the previous paper. The manner in which fault and arc resistances were introduced in the circuit for the case of the double line-to-ground fault is illustrated in figure 3. The point of application of the fault was selected and the fault duration was modified so that each phase would clear at its earliest normal current zero. The point of application of the fault was then shifted successively until the maximum recovery voltage of either phase was obtained. It is data secured in this manner that are plotted in the curves given in a subsequent section. The scope of this study

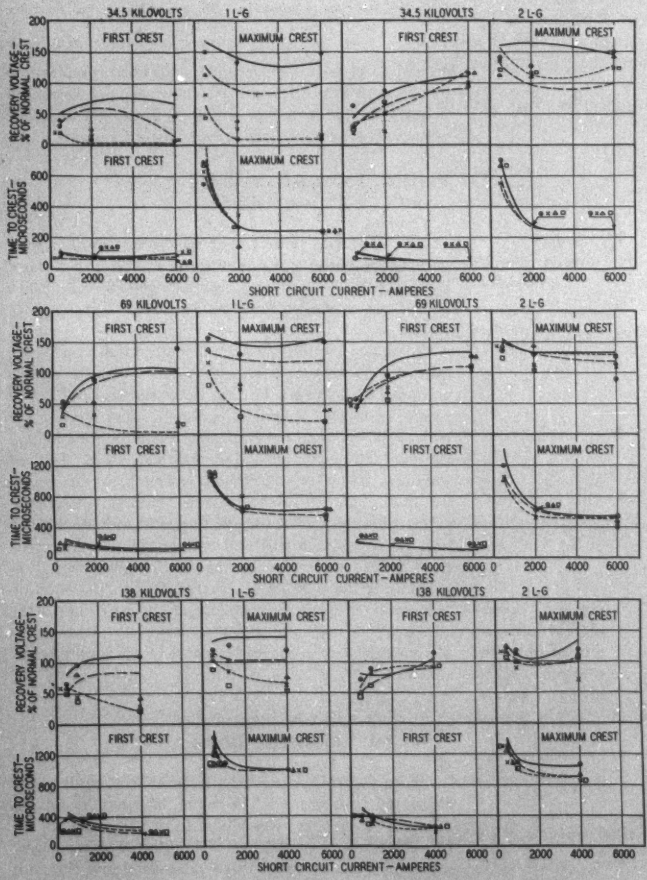

Figure 6. Recovery voltage curves and plotted points for the nine selected systems

Group I—Solid grounding. Voltage magnitude and time to crest plotted as a function of three-phase symmetrical short-circuit current at the sending end

Notation: 1-*L*-*G*, single line-to-ground fault; 2-*L*-*G*, double line-to-ground fault

	Load	Arc Resistance	Tower-Footing or Ground Resistance (Ohms)
———	Yes	No	0
— —	Yes	Yes	0
– – –	Yes	No	100
○	Yes	No	0
Δ	Yes	No	25
X	Yes	Yes	25
□	Yes	Yes	100

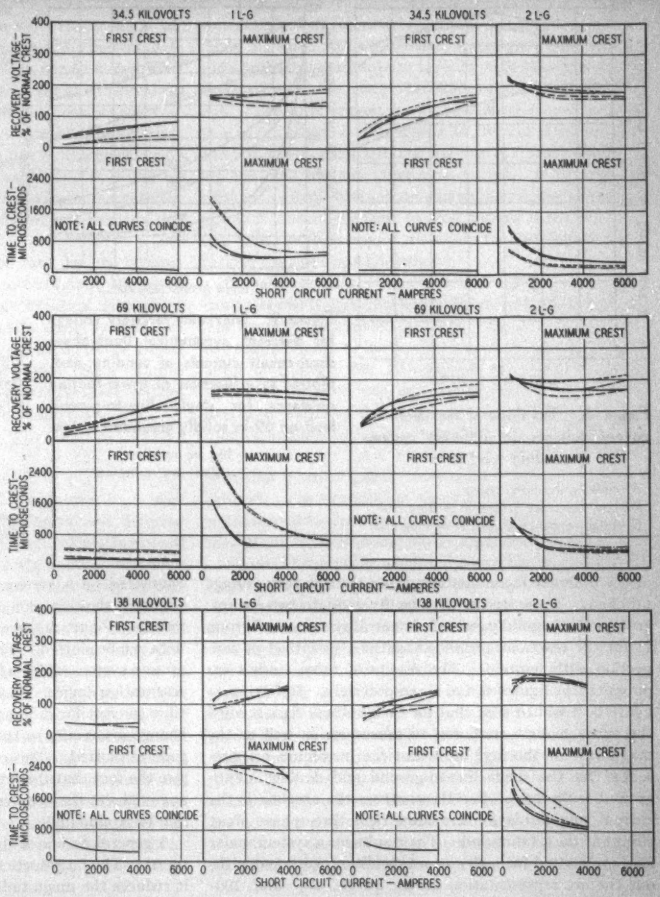

Figure 7. Recovery-voltage curves

Group II—Reactance grounding. Voltage magnitude and time to crest plotted as a function of the three-phase symmetrical short-circuit current at the sending end

Notation: 1-L-G, single line-to-ground fault; 2-L-G, double line-to-ground fault

	Reactance Value	Arc Resistance
———	Low	No
– – – –	Low	Yes
— — —	High	No
— — —	High	Yes

was limited to the cases in which the faults were cleared at normal current zero without restriking of the arc.

Typical recovery-voltage curves obtained from the a-c calculating-board study are plotted in figure 4. These curves show definite first crest and maximum crest. In some cases, second and third crests were of approximately the same magnitude, and in these cases the second crests were used as they are more severe for an insulation-recovery curve that has a rising slope.

Results of A-C Calculating-Board Studies

In an investigation of this type it is not practical to consider the application of the fault at several points on the system. A preliminary study was, therefore, made to determine the effect of moving the fault along the line. Figure 5 shows the results of such a study for a 90-mile, 138-kv system capable of supplying a symmetrical three-phase fault current of 826 amperes at the sending end and with no load on the system. The recovery-voltage results for the single line-to-ground fault are for zero tower-footing resistance and the results for the double line-to-ground fault are for 33-ohm tower-footing resistance. When it is considered that both time and magnitude are of importance in studying the effect of recovery voltage on a piece of apparatus, it will be seen that although the magnitude varies as the fault is moved along the line, the time also varies. Considering the shape of insulation-recovery voltage curves for certain specific pieces of apparatus, it was concluded that the recovery-voltage conditions were about as severe for faults at the sending end as at any location along the line. Therefore, the fault at the sending end was considered to be representative and was used in the general studies.

Based on the selected systems, a series of studies was made on the a-c calculating board to determine the effect

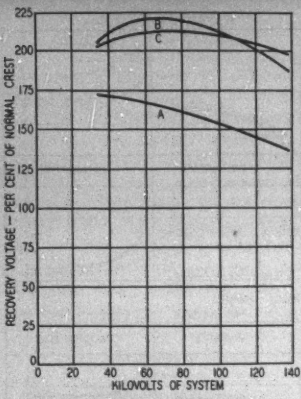

Figure 8. Envelope of maximum recovery voltages for different system-grounding conditions

A—Solidly grounded system
B—Low-reactance ground at sending end
C—High-reactance ground at sending end

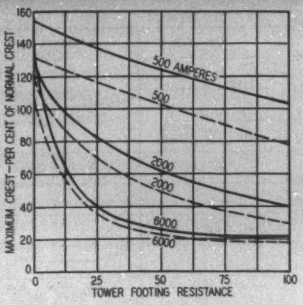

Figure 9. Maximum recovery voltage for different symmetrical three-phase short-circuit currents at sending end, plotted as a function of tower-footing resistance for single line-to-ground fault on 69-kv solidly grounded system

——— No arc resistance
– – – – With arc resistance

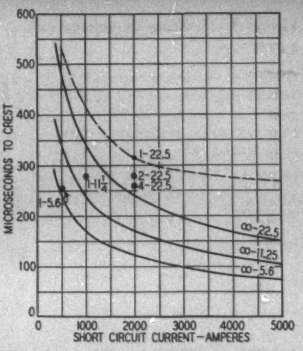

Figure 10. Recovery-voltage time to crest for 34.5 kv system plotted as a function of symmetrical three-phase short-circuit current

——— Infinite number of lines of different lengths
– – – – Finite number of lines aggregating 22.5 miles
Example: Notation 1–22.5. First figure—number of circuits; second figure—aggregate miles of line

of the different factors entering into the recovery-voltage problem. These studies may be divided into two groups; group I for the solidly grounded neutral systems, and group II for the reactance-grounded systems, described in connection with figure 1. The results of these studies are presented in figures 6 and 7, respectively. Referring to figure 6, it will be seen that for each voltage class studied the times to first crest and to maximum as well as the magnitude of the first crest and the maximum are presented for the single line-to-ground and double line-to-ground fault cases. For these curves the abscissa is the current magnitude for a symmetrical three-phase short circuit at the sending end. The results for a system under load are plotted for each current condition, with and without the arc representation device for 0-, 25,- and 100-ohm tower-footing resistance. For comparison, one study with no load and zero arc and tower-footing resistance is plotted. The arc representation device is of the same general type as described in the previous paper making use of Rectox resistors to simulate the arc characteristics of a deion protector tube. The Rectox resistor was adjusted to give approximately 20 per cent of line-to-neutral voltage at the peak of the symmetrical short-circuit current wave. This value was chosen to give the maximum effect of this factor as the minimum effect is shown by the condition of load and no arc representation device.

Figure 7 presents the results of similar studies made on the same systems except with reactance grounding. The system arrangement with respect to grounding is shown in figure 1.

The recovery-voltage data in figures 6 and 7 can be plotted in a large number of ways, depending upon the point under investigation. It is of general interest to know the maximum recovery voltage that can be encountered on a system when all the factors are varied. Figure 8 shows a plot of the envelope of such maximum values. Figure 9 shows another manner in which the data can be plotted. This example is for the 69-kv solidly ground system with load and with and without the arc representation device. It will be seen from figure 6 that the time to crest for different fault-resistance values does not change materially so that the significant factor is magnitude as plotted. This curve has been included to emphasize the fact that the introduction of tower-footing resistance reduces the recovery-voltage magnitude for a single line-to-ground fault.

A general review of the results of these studies is of interest. The introduction of load has little effect although it reduces the magnitude and decreases the time to crest slightly. The introduction of arc resistance in the solidly-grounded system reduces the magnitude for both single and double line-to-ground cases but very materially for the former. The time to crest is not influenced very much. Tower-footing resistance lowers the magnitude and the greater the resistance the larger this effect. Again the time is not affected.

Reactance grounding materially increases the magnitude. The introduction of resistance tends to lower the magnitude for both values of reactance grounding but the effect is not marked. The time to maximum crest for the single line-to-ground fault is considerably increased with the introduction of reactance.

On the solidly-grounded neutral system the magnitudes are very close for the single and double line-to-ground faults. For the reactance-grounded systems the magnitude of the double line-to-ground fault is considerably higher than for the single line-to-ground case.

When a comparison of the results of the tests on sys-

tems with line connected is made with the severity of tests for circuit breakers,[2] it is found that the magnitudes are lower. The largest difference is in the time to crest, this being 6 to 12 times as much as for the circuit-breaker test. If the aggregate length of line is increased over the values used in the studies, the spread in the time to crest will be still greater. The effect of line is, therefore, very important in the recovery-voltage problem. It is also of interest to note that the envelope of maximum magnitudes decreases for the higher system voltages as a result of the greater lengths of connected lines.

Since the system recovery voltage has a decided bearing on the economical design of the protector tube and since the laboratories for testing circuit breakers give more severe recovery voltages than found on actual systems, we believe the data presented will be very useful in the preparation of a test code for protector tubes. Such requirements might be specified as magnitude of recovery voltage and time to crest for given short-circuit currents.

Effect of Other Factors

Although a large number of different factors have been investigated for different fault conditions and different conditions of grounding in the a-c calculating-board studies, there are, nevertheless, certain other pertinent factors that enter into an application which must be considered. The analytical method of solution is useful in considering some of these factors, such as the number of circuits and their total capacitances, the latter being proportional to the aggregate length of line. In order to illustrate the effect of *total capacitance* or aggregate length of line, figure 10 has been prepared and it shows that the time to crest is very materially affected. For example, for the case of a system capable of supplying a symmetrical three-phase short-circuit current of 2,000 amperes and with the capacitances equivalent to 5.6 miles of line lumped at the sending end, the time to crest is approximately 120 microseconds whereas with the capacitances of 22.5 miles of line lumped at the sending end the time to crest is approximately 240 microseconds. It is seen that the severity increases with the decreased aggregate length of line and approaches a maximum severity with zero line, which is the case for the circuit-breaker sectionalizing application. The time to crest for a single-phase circuit is equal to $\pi \sqrt{LC}$, where L corresponds to the source inductance and C to the total capacitance assumed lumped at the sending end, and line reactance is neglected. If the time to crest for a given short-circuit current and aggregate length of line is known, the time to crest for any other length of line would increase approximately as the square root of the ratio of the aggregate line lengths.

The effect of *length of line*, that is straightaway length as contrasted with aggregate length, is brought out in figure 10. The condition of capacitance being lumped at the sending end for 22.5 miles of line is plotted and compared with the effect of a single line 22.5 miles long. This, in effect, shows the range of time that can be expected for a given aggregate length of line for anything from a single to an infinite number of lines. Points are also shown for two and four lines for the 2,000-ampere condition. It will be seen that when length is increased the time to crest is increased. The severity of recovery voltage is inversely proportional to the times to crest given in figure 10 as the magnitude remains practically constant for this case.

Figure 11 shows the results of a number of calculations[1] based on the wave theory, for the nine selected systems previously studied. These calculations are made for single line-to-ground faults at the sending end with the sending and receiving ends solidly grounded. These do not consider the effects of load, initiating transients, or tower-footing or arc resistance. They do, however, illustrate the general shape of the recovery-voltage curve and give a close check for the a-c calculating-board studies for maximum crest. In the curves of figure 11 the magnitude of the "first crest" at the shorter times is also of interest as it is probably a lower limit of the values that can be expected on the system, as the transients arising from the initiation of the fault are not included. The results of the a-c calculating board study are probably an upper limit as

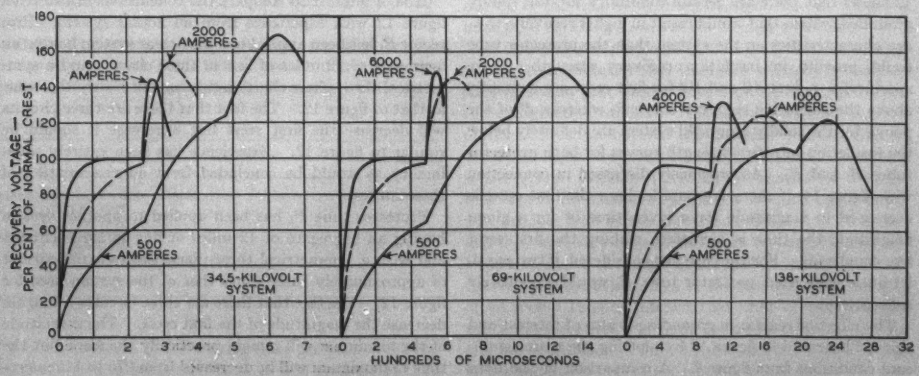

Figure 11. Calculated recovery voltages for single line-to-ground fault on solidly grounded systems

these include the effect of initiating transients and some extraneous oscillations introduced by the networks. The actual determining conditions are probably between these two limits but the relative position has not been definitely determined as it is not of immediate interest in presenting broadly the results of this series of studies.

It is of interest to note the effect on the first crest of varying the length and number of lines, as previously was done in connection with the effect on the second crest in discussing figure 10. For example, if four lines of the same length were used for, say, the 2,000-ampere case the recovery-voltage curve would approximate that of the 500-ampere case, since one may assume four fictitious systems supplying 500-ampere symmetrical short-circuit currents operating in parallel to give the 2,000 amperes.

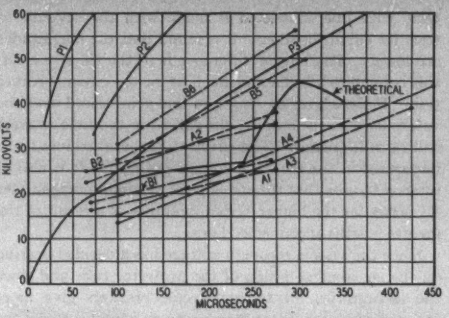

Figure 12. Comparison of system recovery voltage and insulation recovery strength for deion protector tubes for 34.5-kv solidly grounded system supplying 2,000 amperes three-phase short-circuit current at sending end

P_1, P_2, P_3—Insulation recovery strength for deion protector tubes of identical design except for increased bore for higher subnumerals
B6, B5, etc.—System-recovery voltage
Nomenclature: *A*—Single line-to-ground fault
B—Double line-to-ground fault
1—Solidly grounded system, arc resistance
2—Solidly grounded system, no arc resistance
3—Low-reactance grounded system, arc resistance
4—Low-reactance grounded system, no arc resistance
5—High-reactance grounded system, arc resistance
6—High-reactance grounded system, no arc resistance

Part II

Application of the Data

It is the purpose of this section to show broadly how the recovery-voltage data can be used in the application of apparatus to a system. Although the recovery-voltage data presented is useful in a large number of applications, the particular application of the deion protector tube will be taken as an illustration. The case of the 34.5-kv solidly grounded system with 22.5 miles of transmission line with a symmetrical three-phase short-circuit current of 2,000 amperes at the sending end has been selected. These data are plotted in the form of recovery-voltage magnitude-time curves as illustrated in figure 12. The points joined with broken lines are for the first crest and maximum overshoot taken from the general curves of figures 6 and 7. The particular fault and arc resistance condition is identified by the notation on the figure. In figure 12 there is also plotted the calculated curve taken from figure 11. There are also plotted curves P_1, P_2, and P_3, which are the insulation recovery-strength curves for three different deion protector tubes with different inner bores but the same fiber length. An examination of the curves of figure 12 shows that there are certain conditions for the solidly grounded system that would result in higher recovery-voltage characteristics on the system than the protector tube could provide in insulation recovery strength. More specifically, points *A*2 and *B*2 for first crest are definitely above the insulation-recovery curve P_3 whereas all of the points for the solidly grounded system are definitely below the insulation recovery-strength curves for both protector tubes P_1 and P_2. As previously discussed in connection with figure 11, if there are parallel lines the first crest is decreased in magnitude for a given time or for a given magnitude the time is increased, making the first crest less significant. For the case just considered, if two parallel lines were used protector tube P_3 would be entirely satisfactory.

The effect of reactance grounding is also of interest and this is illustrated in figure 12 by plotting the more significant conditions from figure 7. A comparison of the data from figures 7 and 12 shows for the single line-to-ground fault, that the interruption problem diminishes as the neutral reactance is increased. It will further be noted for the double line-to-ground faults with the higher value of reactance that the severity is increased very materially over that of the solidly grounded system to a point that it approaches protector tube P_3.

Correlation of System Recovery Data and Operating Experience With Deion Protector Tubes

It is of interest to compare the conclusions drawn from figure 12 with experience from an actual system. Protector P_1 has been applied to a particular system having an aggregate of 22 miles of line in three circuits and a symmetrical three-phase short-circuit current nearly the same as that of figure 12. The fact that there are three circuits will decrease the first crest but otherwise it should be similar to figure 12. Experience has been entirely satisfactory as would be concluded from an examination of these curves.

Protector tube P_1 has been applied to another system having an aggregate of 12 miles of line in three circuits and with a symmetrical three-phase short-circuit current of approximately three times that of the system used for figure 12. The fact that there are three circuits will again decrease the magnitude of the first crest. The magnitude of the maximum will remain practically the same but the time to maximum will be decreased from 275 to 115 microseconds. This is because, as previously shown, the time

varies as $\sqrt{LC}$. L varies inversely as the short-circuit current and C varies directly with the aggregate line length. The line length is decreased in the ratio of 12 to 22.5 which will decrease the time as the square root of this ratio or to 73 per cent; also the fact that the source inductance has decreased to one-third will decrease the time 58 per cent, making a total reduction of 42 per cent. Experience has again been entirely satisfactory as would be concluded from an examination of the curves of figure 12.

In the case of protector tubes P_1, P_2, and P_3, shown on figure 12, the designs are identical except the bore is increased for the higher subnumerals. It will be noted that the insulation recovery characteristics of the protector tube are lower as the bore increases. In the normal operation of the deion flashover protector tube successive operations tend to increase the bore. It has been recognized in the application that after a number of operations the bore will eventually erode to a diameter that will cause the protector to fail. This is illustrated by a comparison of curves P_1, P_2, and P_3. For example, if protector tube P_1 leaves the factory with a definite inner bore it is quite conceivable that after a number of operations the bore will increase to approach the characteristics of protector tube P_2 or even protector tube P_3. It is, therefore, seen that eventually the protector will fail to clear.

It is believed that there has been undue apprehension in connection with the erosion of the protector tube for the practical application. Through the co-operation of the Interstate Power Company it has been possible to secure direct measurements of this factor on the oldest extensive application of protector tubes. This experience was obtained on the 66-kv line joining Dubuque and Clinton, which consists of 47 miles of single-circuit line with flat configuration and seven miles of double-circuit line with vertical configuration. Ground wires are not used and the line is insulated with four ten-inch units, spaced five and three-fourths inches. The line was placed in service August 15, 1926, and in six years time, before the deion protector tubes were installed, there were 277 interruptions that could be traced to lightning. This is an average of 46 interruptions per year. The large number of outages per year is direct evidence that there were and are a large number of strokes to the line per year.

Deion flashover protector tubes were installed on this line in August 1932. The following is an interruption record after the installation was made:

Period	Interruptions
August 1932 to December 1, 1932	0
Year 1933	3
Year 1934	0
Year 1935	3
Year 1936	8
January 1, 1937 to August 20, 1937	2
Total	16

This is an average of 3.1 interruptions per year which corresponds to a reduction of 15 to 1. An analysis of these explained 15 of the 16 interruptions. In the year 1933 two

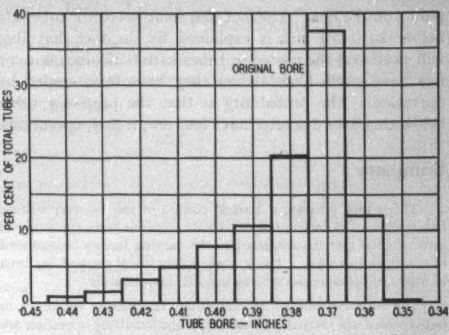

Figure 13. Erosion data obtained after five years' operation of deion protector tubes installed on the Clinton-Dubuque line of Interstate Power Company

protector tubes were destroyed due to high surge current estimated at from 75,000 to 100,000 amperes. In the latter part of 1935 and the early part of 1936 there was a sudden increase in the number of outages which led to an investigation. The outstanding improvement in the performance of the lines justified at times shutting down the station at Clinton although the original application assumed it in operation. This change resulted in reducing short-circuit current at the Clinton end of the line to approximately one-third of the minimum rating of the deion flashover protector. An analysis of the outages for 1935, 1936, and 1937 indicated that all these failures occurred within a few miles of the city of Clinton. An analysis of this particular condition indicates that with the lower short-circuit currents the recovery-voltage strength of the protector tube is lower than the recovery voltage on the system with the result that the protector tubes failed to clear. In August 1937 the protector tubes on the Clinton end covering a distance of approximately 20 miles, were replaced with protector tubes having higher insulation recovery strength. No outages have since resulted on this line up to the time of writing although there have been a number of lightning storms in the vicinity of the line.

In changing the protector tubes a program was carried out by the Interstate Power Company whereby it was possible to obtain bore measurements on all of the protector tubes originally installed. This allows a detailed analysis of the increase of bore or the decrease of insulation-recovery strength as a result of a large number of operations in five years. A limit of 0.45 inches was set for the bore that would be satisfactory for the original application. The original bore of the protector tubes was 0.375 inches and they were very close to this when they left the factory. Figure 13 shows the range of bores after the five years of operation, these being given to the nearest one-hundredth of an inch. It is of interest that none of the protector tubes have reached the limit set as satisfactory for the original application. Only 2.7 per cent have reached 0.43 inches and five per cent have reached 0.42 inches. The protector tubes that were eroded the most were installed at high

points on the line. The fact that some protector tubes are below the 0.375 inch is explained by the fact that fiber will swell and the protector tubes with 0.375 inch bore or less have swelled more than they have been eroded by operation. The probability is that the protector tubes below this bore diameter have had few, if any, operations.

Summary

1. This paper presents a general picture of the recovery-voltage characteristics of transmission systems obtained from the study of nine selected systems subjected to the varying factors encountered in practical operation. The a-c calculating-board method has been of major importance in carrying out this investigation.

2. The recovery-voltage characteristics of systems subjected to faults which are cleared without a line-sectionalizing operation are much less severe than that for the clearing of the last circuit breaker on a bus. This difference is so marked that advantage should be taken of it, in the design of certain pieces of apparatus.

3. The method of analysis and the data presented should be of value in the application of certain pieces of apparatus and in the preparation of test codes for specific devices.

4. This general analysis is of immediate interest in connection with the application of protector tubes, and operating experience with this device supports the analysis. Erosion of the protector tubes due to operation is such that the insulation-recovery characteristics are not changed at an impractical rate.

Acknowledgments

The authors wish to acknowledge the co-operation of Messrs. W. Wisco and H. Chambers of the Interstate Power Company in securing the valuable data on the performance of the protector tubes on their system. They also wish to acknowledge the helpful suggestions of their associates, particularly Mr. R. L. Witzke who conducted the a-c calculating-board studies and prepared the data presented.

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Discussion

W. J. Rudge, Jr. (General Electric Company, Pittsfield, Mass.): Messrs. Evans and Monteith have made a valuable contribution in their paper on the recovery-voltage characteristics of transmission systems. Since their studies were conducted on an a-c calculating board, it will be of considerable interest to compare the results given in their paper with results which were obtained by actual measurements in staged field tests.

In figure 8 a plot is given of recovery voltage crest in per cent of normal line-to-neutral voltage. The recovery voltage is given for both solidly grounded neutral systems and systems grounded through reactors. This curve indicates that on solidly grounded neutral 115-kv system the recovery voltage will rise to about 150 per cent of normal. We have recently completed tests on a 115-kv system where the recovery voltage measurements varied from 115 to 178 per cent of normal. We have also made tests on a 26.4-kv system which was grounded through resistance where the recovery voltage measured to ground varied between 115 and 187 per cent of normal. Similar tests on a 33-kv system with neutral grounded through resistance give recovery voltages varying between 100 per cent and 185 per cent of normal. Tests made on a 33-kv isolated neutral system give values ranging between 100 and 170 per cent of normal.

Referring to figure 11 of the Monteith-Evans paper, it may be noted that the highest values of recovery voltage occur with the lower currents on the low-voltage system and on the higher-voltage system the highest recovery voltage occurred with the larger currents.

Referring again to our actual field tests, the data on each of the four separate field tests mentioned above indicates that the highest recovery voltage occurs with the lower values of short-circuit current. Further data may, however, show that it is possible to obtain as high recovery voltage with large currents as have been obtained with the lower values. In the field tests the highest values of recovery voltage occurred with currents ranging between 500 and 1,500 amperes whereas the lower values of recovery voltage were for currents in the order of 3,000 amperes.

In giving these results, we do not intend to infer that low values of recovery voltage do not occur with low values of current, as there are many instances where the recovery voltage varied between 100 per cent and 150 per cent of normal in the low range of short-circuit currents. The data from field tests cited above show the highest values of recovery voltage occurring in the range of currents obtained.

In other words, this comparison of field data with the data obtained on the a-c calculating board, show that the results obtained from the board can be no more accurate than the basic data upon which the board is set up. It is therefore essential to have an adequate background of field tests before accurate results can be expected from the a-c board.

On the basis of the field tests, it appears that the crest recovery-voltage characteristic, when plotted against system voltage, is almost a flat line, whereas in figure 8 of the Monteith paper, the curve indicates that for the higher system voltages the maximum recovery voltage has a downward trend.

We note in figure 12 of the Evans-Monteith paper that the characteristics for the protector tubes *P*-1, *P*-2, and *P*-3 do not extend to the region near normal voltage so that when comparing the recovery characteristic of the system with recovery characteristic of the tube, one would infer that the rate at which the voltage rises at the early part of the curve has no effect on tube operation unless the voltage rose at least to the point where the tube characteristic curves begin. We would like to have the authors explain whether these curves are the limit of the data which has been taken on the tube, or whether we have correctly interpreted their results. Tests which we have made on tubes indicate that it is essential for the characteristic curve to be extended back to voltage equal to or even less than normal, as tubes may fail to clear because of too rapid rate of voltage rise, rather than long time in which the peak value of the circuit recovery voltage occurs.

R. C. Van Sickle (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Although the data presented in this paper applies specifically to protector-tube application, it has additional interest to those associated with high-voltage circuit breakers and their application, as is suggested by the authors. The recovery-voltage characteristics of the typical circuits on which breakers are applied cover a wider range and unfortunately the upper limit is not as well fixed as in the case of flashover protectors because the minimum amount of effective capacitance is more difficult to determine. That the effects of lines and loads greatly reduce the severity of the voltage recovery characteristics has already been demonstrated by measurements taken during field tests on circuit breakers but such data are naturally limited and apply to the particular conditions existing for the test. Consequently, the data presented in this

paper is a welcome addition to the general fund of information on the severity of some of the service conditions which may be imposed on circuit breakers.

The characteristics imposed on a tube at the far end of a line are the same as those on a breaker opening at the end of the line. Likewise, the characteristics imposed on a tube at the near end of a line are the same as the characteristics imposed on a circuit breaker opening one line with another line still connected to the same bus.

Since the lengths of the lines have been chosen as short as are typical for the corresponding voltage, the effects produced can be regarded as being the minimum which would normally be expected. A 138-kv circuit having a three-phase short-circuit current of 500 amperes might impose, on the circuit breaker during a single line-to-ground fault, a voltage crest of 190 per cent which occurs about 110 microseconds after current zero. This corresponds to a voltage-recovery rate of 1,020 volts per microsecond. The data in this paper shows that a parallel line would reduce the maximum voltage from 190 per cent to 135 per cent and the rate from 1,020 to 104 volts per microsecond.

Other data shows that locating the circuit breaker at a substation fed by a 90-mile 138-kv line with the neutral solidly grounded and a three-phase short-circuit current of 826 amperes, subjects it to a maximum voltage 160 per cent of normal and a voltage-recovery rate of 89 volts per microsecond. These conditions are approximately the same as those encountered with a parallel line.

These are only a few of the interesting comparisons which can be made by use of the data presented in this paper.

D. C. Prince (General Electric Company, Philadelphia, Pa.): This paper naturally divides itself into two parts; (1) methods of analysis of circuits to obtain the form of recovery-voltage characteristics; (2) the nature of the interrupting characteristics of the expulsion tube with reference to recovery voltages impressed upon it.

There are several methods already in use for determining recovery voltage, ranging all the way from straight calculation through the calculating board methods, discussed by these authors, and ending up at the other extreme with field tests by cathode ray oscillographs. With the addition of the authors to this situation there are available methods of determining recovery voltage forms for practically all conditions.

The second half of the paper is outstanding in that it represents the most exact correlation yet established between any circuit interrupting apparatus and the recovery voltage of the circuit upon which it must work. In the body of the paper, it is stated that the important elements of recovery voltage are the length of time to reach the crest value and the magnitude of that crest value. This statement is not supported by the test information shown. Referring to figure 12, it appears that the variation of strength with time for three expulsion tubes is shown in the curves P_1, P_2, and P_3. If the recovery voltage lies wholly below any one of these three curves, the corresponding design of expulsion tube may be expected to operate satisfactorily.

If, on the other hand, there is a point where a curve of recovery voltage crosses one of these lines P_1, P_2, or P_3, as the case may be, at that point the tube will break down. It would be interesting to know how these curves P_1, P_2, and P_3, were obtained since if this statement of the case is correct, this represents the most accurate correlation between the behavior of any circuit interrupting device and the recovery voltage characteristics of a system yet published.

Above and below the portions plotted in figure 12, it is presumed that waves likely to be obtained would not cross the portions of these lines not plotted, but this could be judged with considerably more assurance if the lines were extended particularly in the direction of shorter times.

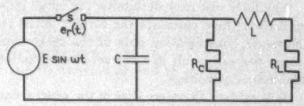
C. N. Weygandt (University of Pennsylvania, Philadelphia): I note that in the method used by the authors an elaborate switching scheme for the cathode ray oscilloscope is required in order to record the high-frequency transients, and also that when the capacitance of the actual circuit is low capacitance of leads and so forth becomes a source of trouble. I should like to suggest an equivalent circuit which may in some cases avoid these difficulties. Suppose that the circuit of figure 1 is to be studied.

The voltage across the switch s can be obtained as the time function corresponding to the operational expression:

$$e_r(t) = \frac{E}{L}\,\frac{p\omega}{p^2+\omega^2} \times \frac{1}{pC + \frac{1}{R_c} + \frac{1}{R_L + pL}}$$

Let us construct an equivalent circuit such that its operational impedance is the reciprocal of that of the original circuit. The inductance now has a value numerically equal to the capacitance in the

Figure 1. Original circuit

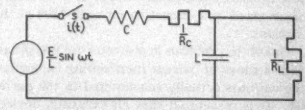


original circuit and the capacitance is equal to the original value of inductance and the resistances are reciprocals of their original values. The current which flows when the switch is closed at the instant $t = 0$ is:

$$i(t) = \frac{E}{L}\,\frac{p\omega}{p^2+\omega^2} \times \frac{1}{pC + \frac{1}{R_c} + \frac{1}{R_L + pL}}$$

which is identical with the voltage across the switch in the first circuit. Moreover by reducing the frequency of the applied voltages and consistently altering the values of the parameters, the natural frequency may be reduced so that it may be recorded with an ordinary magnetic oscillograph. Also since the applied voltage in the

Figure 2. Equivalent circuit



equivalent circuit represents the interrupted current in the actual circuit it should be more easily possible to simulate interruption when the current is not zero, nonlinear arc characteristics and the like. A numerical example follows:

Given an original circuit with the constants in the left-hand column, the equivalent circuit will have the constants in the right-hand column:

Original Circuit			Equivalent Circuit		
0.25	millihenry	$= L$	25	microfarads	$= L$
0.00025	microfarad	$= C$	2.5	millihenrys	$= C$
0.01	ohm	$= R_L$	10^8	ohms	$= 1/R_L$
10^5	ohms	$= R_c$	0.01	ohm	$= 1/R_c$
377	per second	$= \omega$	0.377	per second	$= \omega$
4×10^9	per second	$= \frac{1}{\sqrt{LC}}$	4,000	per second	$= \frac{1}{\sqrt{LC}}$
60	cycles per second	$= f$	0.06	cycle per second	$= f$

C. Concordia (General Electric Company, Schenectady, N. Y.): In the past few years there has been a large number of papers written on recovery voltage. One of the striking features of these papers is that there are apparently two different viewpoints about the relative importance of the various factors involved in recovery voltage calculations. One group leaves us with the impression that the important factors are the traveling waves and their reflections, the other that the important factors are the natural frequencies of the circuit. The present paper by Messrs. Evans and Monteith appears to fall in the latter class.

There need be no essential or theoretical conflict between the two points of view. On the other hand, as the traveling waves depend on the surge impedances and transmission distances, while the natural frequencies depend in practice on lumped circuit approximations to the actual system, one may arrive at different conclusions regarding a particular system by the two methods of approach. It is essential to examine carefully each case to determine what must be considered and what can safely be neglected.

One may construct a lumped circuit which possesses the same first, second, etc., natural frequencies and the same steady state characteristics as the actual circuit. In a practical case one will match the circuit frequency response characteristics only up to some limiting frequency. The initial response of such a circuit to an impulse will bear no relation to the initial response of the system.

Similarly one may determine the surge impedances of the system and from them calculate the correct initial response to an impulse. However, consideration only of the surge impedances and reflection times will not result in a correct determination of the oscillations of the recovery voltage.

It is evident therefore that in the general case both effects must be taken properly into account. In some cases, however, the reflection times are so short that the circuit behaves very nearly like its lumped circuit equivalent. In other cases the reflection times are sufficiently great so that the voltage during the period of interest may be determined entirely from the surge impedances. Still more significant is the fact that for some applications the initial response (e.g., the initial rate of use of voltage) is the most important factor, while for other applications the magnitude of the voltage swing may be the most important. In the general case again the entire recovery characteristic must be considered.

L. G. Smith (Consolidated Gas, Electric Light, and Power Company of Baltimore, Baltimore, Md.): Data of the type included in this paper are of real interest to those companies applying deion protector tubes and expulsion protective gaps. Our company has made several applications of these tubes on our 13.2-kv lines and a few isolated applications at 110 kv. Details of these installations are covered in a discussion on page 1509 of the 1937 AIEE TRANSACTIONS.

One of the problems in protector-tube applications is to obtain tubes with a range of current interrupting capacities, within which range the currents actually encountered in the particular application will lie. It is recognized that all expulsion devices have two limits on their current interrupting capacity:

1. The maximum current, which is limited by the bursting strength of the tube notwithstanding the pressure produced by the high currents.

2. The minimum current below which sufficient pressure is not developed to extinguish the arc.

It is understood that the minimum current rating of an expulsion device depends to a large extent upon the rate of rise of recovery voltage. For a given bore diameter the lower the rise of recovery voltage the lower the minimum current that can be interrupted.

Since protector tubes are applied by connecting them from each phase to ground, the ground connection usually being a common connection for all three phase tubes the maximum current interrupting capacity must be sufficient to clear a phase-to-phase fault if two tubes are discharging simultaneously. On the other hand, the minimum interrupting capacity of the tube is determined by the maximum ground resistance, if a single tube discharges. As ground resistances may at times be high and also vary over considerable ranges of values due to weather conditions, it is frequently necessary to use a so-called multiplex installation in which phase tubes of high current interrupting capacity are installed in each phase and a single ground tube installed in the common ground connection, this tube having a lower current rating. If more definite information were available concerning the probable rates of rise of recovery voltages on various systems it should be possible to extend the application of tubes and possibly eliminate the multiplex connection in many instances. Therefore, information on this point is desired by the industry.

R. D. Evans and **A. C. Monteith:** The principal objects of our paper are to provide (1) a general picture of the recovery-voltage characteristics of transmission systems which has been obtained with the aid of the a-c calculating board and (2) to illustrate the use of the recovery-voltage data in connection with the application of a specific arc-interrupting device, the protector tube. This is the first time that a broad picture of the recovery-voltage problem on transmission systems has been presented. Until such a picture is available and generally understood, refinement in methods of analysis and greater detail in the characteristics of the device are of secondary consideration. A review of the discussions shows a general agreement with the importance of our objectives and the interpretation of the data presented. This general viewpoint should be kept in the mind in considering the replies to the specific discussions.

We fully agree with Mr. Concordia that there is no essential or theoretical conflict between recovery-voltage calculations by traveling waves and by networks with lumped constants, provided the network constants have been suitably chosen and provided that both types of calculation have been carried to a fair degree of refinement. Both methods have been discussed and used in the paper, one method providing a check against the other. It is the particular advantage of the method using networks with lumped constants that makes possible the use of the a-c calculating-board method which provides a practical form of solution for general analyses, the results of one such study being presented in the paper under discussion. This point of view was discussed in greater detail in our paper entitled "System Recovery Voltage Determination by Analytical and A-C Calculating-Board Methods" presented at the 1937 summer convention in Milwaukee.

Mr. Van Sickle's discussion is of value in that it shows the application of the system recovery voltage data to another specific apparatus problem, the circuit-breaker problem.

Mr. Rudge has presented certain results of field tests and made comparison of measured voltage magnitudes with those of figure 8 of the paper. In this connection it is pertinent to observe that the recovery voltages of figure 8 are definitely associated with the figures 6 and 7 which incorporate time as well as magnitude. In figure 5 we have shown that higher recovery voltages than those plotted in figures 6, 7, and 8 can appear on the system but those voltages were generally associated with considerably longer time so that they were not considered as significant as the voltages plotted. It is, therefore, unfortunate that Mr. Rudge has not given the times associated with the voltage magnitudes presented in his discussion so that a detailed comparison could be made. Mr. Rudge's discussion raises the question as to whether more severe conditions are met in the field than are indicated in the paper. This question cannot be answered unless the times associated with the recovery voltage magnitudes are also presented. Results of tests given in the previous paper just referred to, together with the results of other tests, give recovery voltage magnitudes and times checking closely with the values given in the paper under discussion when these are put on a comparable basis.

Mr. Rudge also makes comparisons between the results of field tests and the data presented in the paper with respect to maximum recovery voltage as a function of fault current and as a function of system voltage. Again the comparisons are not complete unless time as well as magnitude is considered.

In the discussion Mr. Rudge implies, but does not state, that the systems tested fall within the range of systems studied on the a-c calculating board. It would be valuable if more detailed information had been given on the systems tested so that direct comparisons could be made.

Concerning field tests, we have recognized and have emphasized in both of our papers the desirability and necessity of such tests as a means for providing benchmarks. We do feel, however, that, on account of the limitations in making such tests, it is difficult if not impossible by this means alone to obtain a broad grasp of the recovery voltage problem.

Both Mr. Rudge and Mr. Prince have raised the question of the characteristics of protector tubes in the short time range. The object of figure 12 is not to provide a complete picture of the characteristics of protector tubes but instead to illustrate the use of the recovery

voltage data given in the paper in connection with the application of a particular piece of apparatus, the protector tube, giving only the characteristics of tubes essential for this purpose. We quite agree with Mr. Rudge's statement that protector tubes may fail to clear at voltages less than normal crest value which have a "too rapid rate of voltage rise." The operation of a protector tube depends on the tube design and on the characteristics of the circuit. For example, tube *P*-3 would fail at less than normal crest for the particular system considered in figure 12, but tube *P*-1 would obviously give satisfactory operation for the same system recovery voltages. More data is available on the characteristics of protector tubes but this is not believed to be pertinent to the present discussion.

Mr. Prince seems to have misinterpreted our discussion on the application of the data in that he infers that we believe the pertinent point in the recovery-voltage problem is the maximum voltage crest and corresponding time. The basic factor to be considered is the relation of the complete curve of system recovery voltage and the complete curve of insulation recovery voltage. However, the complete curve is rarely needed and usually the conditions may be defined by a few critical points usually describable as first crest and maximum crest. We wish to emphasize the fact that these critical points must be given in terms of voltage magnitude and time, or some pair of related quantities, and cannot be given in terms of a single quantity such as the rate of rise of recovery voltage.

Mr. Prince inquired as to the method of obtaining insulation recovery curve of the protector tubes of figure 12. The points were obtained by measuring the voltage and time on cathode-ray oscillograms when restriking occurred. Therefore, as stated by Mr. Prince, if the system recovery voltage curve crosses the insulation recovery curve, failure will occur at the point of crossing.

Mr. Weygandt has made an interesting suggestion to replace the equivalent network used in recovery voltage studies by a "reciprocal" network in order to avoid the effects of stray capacitance. This is not, however, an important limitation of the a-c calculating-board method. This is due to the fact that it is usually possible to select an equivalent network using high values of capacitance and still obtain the desired natural frequencies. An alternative method is to use different ratios of fundamental to natural frequencies as explained in the closing discussion of our previous paper (see ELECTRICAL ENGINEERING, October 1937, page 1311). It is also important to retain the advantages inherent with the present procedure which permits obtaining in a straightforward manner the transient effects due to the application of a fault and its clearing as well as the effects of subsequent restrikes.

We agree with Mr. L. G. Smith that when a broad knowledge of the characteristics of recovery voltages of systems is obtained and when more data on the performance of protector tubes becomes available, a more scientific application of protector tubes will become possible and this in turn will eventually lead to a simplification of the application procedure.

Critical Conditions in Ferroresonance

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Introduction

THE APPLICATION of "ferroresonant" circuits to engineering problems has become increasingly important from both theoretical and practical considerations. While much progress has been made in the general study of ferroresonance, treatment is lacking in an accurate description of, perhaps, the most interesting part of the phenomena, namely, the so-called critical points at which the current suddenly changes in value. From a practical viewpoint, it is this characteristic property that makes ferroresonant circuits useful as sensitive elements in relay and control apparatus. Accordingly, there is a definite need for simple quantitative information that completely predetermines the behavior of the circuit under critical conditions and specifies the required circuit parameters in terms of known quantities.

Of the various methods employed in the study of ferroresonance, the method of graphical solutions presents itself as the most flexible and gives a somewhat better physical picture of the phenomena. On the basis of this method, a simple rule is proposed for the criteria of stability which uniquely determines the critical conditions and permits analytic development of simple formulas defining the critical quantities. An interpretation and discussion of equations bring to light several interesting aspects of the phenomena and point to inaccuracies of previous methods. Various applications of the theory are given.

Review

The ferroresonant circuit consists of elements of resistance and capacitance connected in series with an iron-core inductance. In the study of ferroresonant circuits with a-c applied voltage, rigorous mathematical treatment has been found practically impossible. With certain simplifying assumptions, however, solutions[2-7] have been given which serve in a general sense to describe the nature of the phenomena. Essentially, the methods followed in treating the series circuit (figure 1) require the determination of a functional relationship between the current and the inductance of the iron-core reactor. Under the assumption of sinusoidal variation of current, a continuous voltage characteristic is obtained from the well-known circuit equation,

$$E = I\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}\ , L = \Phi(I) \qquad (1)$$

Several theoretical characteristics are given in figure 2 showing the influence of resistance and capacitance. To attach meaning to the multivalued curves thus obtained, the region in which the voltage decreases with increase of current is designated as unstable since it is physically unattainable. At the extremities of this region therefore, an abrupt change in current takes place as indicated by the dotted lines. The points of sudden transition of current are defined as critical points (1, 2).

It is of particular interest to note that the analytical method provides no means for determining the critical points except by the graphical procedure just outlined. Furthermore, it would appear that the critical points (2) associated with the collapse of current are bounded by the resistance line (IR) since the variable impedance has a minimum value equal to the resistance. This relation, however, is at most approximate and does not hold in general.

The method of graphical analysis, first introduced by Stark,[4] is advantageous because of its simplicity. In this representation, the volt-ampere characteristics of the reactor ($E_L = f(I)$) and the condenser ($E_c = I/(\omega C)$) are employed to determine graphically the variation of the resultant reactive voltage which is given by the difference of ordinates (figure 3). The results are then applied to a modified form of equation 1,

$$E = \sqrt{(IR)^2 + \left(E_L - \frac{I}{\omega C}\right)^2} \qquad (2)$$

and operating characteristics similar to those in figure 2 are obtained.

A refinement of this method, due to Rouelle,[19] requires the separation of the reactor voltage into active and reactive components on the basis of fundamental frequency. A predetermination of the operating characteristics shows good agreement with experimental results; but just as in the previous case, the critical points are not defined.

Method of Graphical Solutions

Historically, the method of graphical solutions represents one of the earliest attempts to explain the multivalued character of ferroresonance and was introduced by Bethenod[1] in a brief treatment on the ideal circuit. The method was later extended to the general circuit by Margand[6] whose interpretation uncovered several important facts, particularly concerning stability. There remain, however, a few considerations that need amplification in order to arrive at a better understanding of the critical conditions.

The graphical solution for the series ferroresonant circuit (figure 1) follows from two independent relations for

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1. For all numbered references, see list at end of paper.

reactor voltage; namely, the volt-ampere characteristic of the reactor,

$$E_L = f(I) \tag{3}$$

and the circuit equation (assuming sinusoidal quantities)

$$E_L = \pm \sqrt{E^2 - (IR)^2} + \frac{I}{\omega C} \tag{4}$$

In the right-hand member of equation 4, the expression under the radical represents an ellipse whose principal axes have values E and E/R, respectively. The second term is a straight line through the origin having a slope

$$\tan \gamma = \frac{1}{\omega C} \tag{5}$$

The sum of the two terms is an ellipse (a fact that may be readily ascertained) whose intersections with the reactor characteristic are the graphical solutions for current (points 1, 2, and 3 in figure 3). The representation in this form because of its component nature permits a simple graphical study of the circuit characteristics with a variation of any of the parameters. To avoid ambiguity of multiple current values, however, it is necessary to distinguish the real or stable solutions from the unstable solutions.

Stability of Current Values

In the previous methods outlined, the question of stability of certain current values arose as a result of the current-voltage relations obtained theoretically. The portion of the curve that was found experimentally nonexistent was classified as unstable, and the curves were modified accordingly to account for the characteristic discontinuity (dotted lines in figure 2). The method of graphical solutions, on the other hand, provides a means to test the stability of the individual solutions and gives, therefore, a better physical picture of the related phenomena.

It was not until Margand's treatment appeared that a reasonable explanation was given concerning the stability of the various points. He showed that points 1 and 2 (figure 3) represented stable solutions, whereas point 3 represented an unstable solution. The following reasons are the basis for this distinction.

Suppose that to leave a stable point, the current suddenly changes by an amount ΔI. The effect of this change upon the circuit may be studied from the relation,

$$(RI)^2 = E^2 - \left[f(I) - \frac{I}{\omega C}\right]^2 \tag{6}$$

If the quantity $[f(I) - I/\omega C]$ increases in magnitude with a slight increase of current, then $(RI)^2$ tends to decrease in accordance with equation 6. The sense of variation of $(RI)^2$, however, is opposed to the assumed change of current; therefore, the point is indicative of a circuit condition in favor of stability. If on the contrary $[f(I) - I/\omega C]$ decreases in magnitude with increase of current, $(RI)^2$ tends to increase, indicating a sense of variation similar to that of the current. Under this condition, the current continues to increase, and the point is characterized as unstable. In a corresponding manner, the same argument could be advanced if the current were assumed to decrease slightly.

The stability of the various points may be established by observing graphically the variation in magnitude of the quantity $[f(I) - I/\omega C]$ as shown by the hatched ordinates in figure 3. Thus, point 3 corresponds to an unstable solution since $[f(I) - I/\omega C]$ decreases with increase of current. The opposite is true for points 1 and 2, hence these are stable solutions.

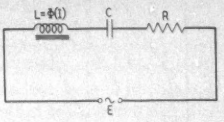

Figure 1. Ferroresonant circuit

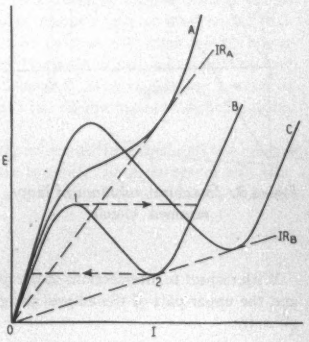

Figure 2. Voltage as a function of current

While the foregoing principle permits a distinction between stable and unstable current values, there appears to be an inconsistency concerning the limiting conditions. For example, take the case where capacitance is the only variable parameter and observe graphically the conditions for the limit of stability. At point 1 the limit of stability takes place when the reactor characteristic and the ellipse are tangent to each other, but at point 2, it occurs when the condenser line $(I/\omega C)$ intersects the reactor characteristic at the maximum value of current, E/R (figure 4). Consequently, with further increase of capacitance, point 2′ which defines a current value less than E/R should be unstable according to the above principle of stability. This, however, is contrary to experience, since it has been observed that the current may decrease considerably beyond the maximum value before instability occurs (see figure 15). Margand's explanation does not account for this effect since it is based upon the aggregate effect of the squared quantities in equation 6, thus concealing a change of sign. More specifically, the criteria for stability should be based upon the points of intersection of the two curves in such a manner that each portion of the ellipse as divided by the condenser line is properly expressed with respect to sign. As a modification, therefore, the following rule is proposed.

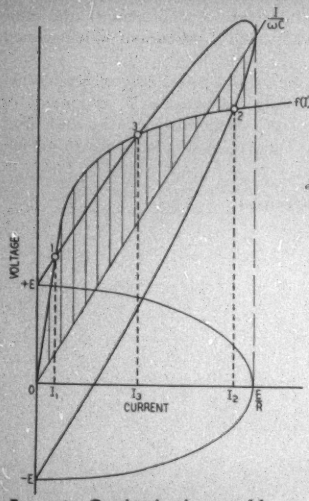

Figure 3. Graphical solutions of ferroresonant circuit

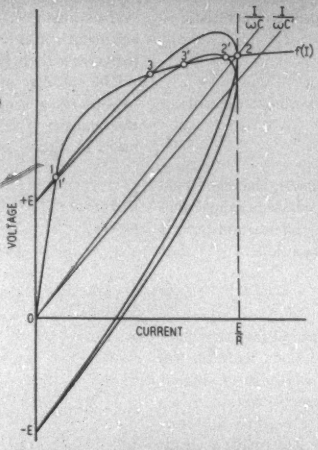

Figure 4. Influence of variation of capacity upon stability; $C' > C$

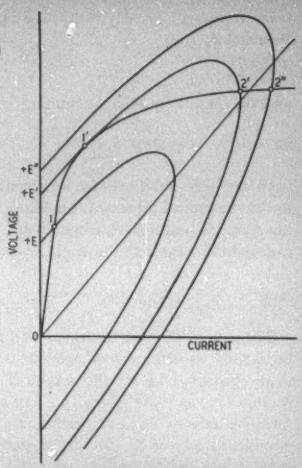

Figure 5. Graphical method of obtaining circuit characteristic, current as a function of voltage

With respect to intersections of the reactor characteristic and the upper part of the ellipse, the graphical solution is given by

$$f(I) = + \sqrt{E^2 - (IR)^2} + \frac{I}{\omega C} \tag{7}$$

Any such point is stable if, for a slight change in current, $f(I)$ correspondingly changes at a greater rate than the right hand member of (7), taking cognizance of the sense of variation of current. Thus, for an increment of current, the ordinate of the reactor characteristic must be greater than that of the upper part of the ellipse, and less, if the current is assumed to decrease slightly.

For intersections associated with the lower part of the ellipse, the graphical solution is given by

$$f(I) = - \sqrt{E^2 - (IR)^2} + \frac{I}{\omega C} \tag{8}$$

and the conditions for stability are reversed. In this case a point is stable if the right hand member of (8) changes at a greater rate than $f(I)$ corresponding to an assumed deviation of current.

An application of the proposed rule will show, as before, that points 1 and 2 are stable, and that point 3 is unstable. Unlike the conclusions reached from Margand's principle, these points retain the same identity throughout their entire range of existence. For example, point 2′ (figure 4) which was previously found to be unstable, is according to the rule (7) a stable point. Furthermore, the limiting conditions for the stable points are geometrically similar, namely, common tangency of ellipse and reactor characteristic (Margand, in a later paper,[12] calls attention to this fact as a "peculiarity," but without giving an adequate explanation). At this point the conditions for stability and instability simultaneously exist, and a slight variation of the parameters in the proper direction will cause a sudden change in current. Graphically, this means that points 1 and 2 are related to the critical conditions of sudden increase and decrease of current, respectively.

Circuit Characteristics

To demonstrate the method of graphical solutions in the study of circuit characteristics, a few illustrations will now be given. The current as a function of capacitance may be obtained by observing the resulting intersections of the ellipse with the reactor curve as the ellipse is rotated clockwise with increasing capacity, having always a vertical tangent at E/R. (The variation of point 3 is unnecessary to observe and is therefore excluded.) If reference is made to figure 4, it is clear that the current, defined by point 2 for small values of capacitance, first increases continuously to a maximum and then decreases until the limit of stability is reached (point of tangency), beyond which the current suddenly falls to a low value defined by point 1. With further increase of capacitance, the current decreases slowly approaching a constant value. Upon diminishing capacitance, the current retraces the same path in the region of low current values and goes beyond the previous point of collapse, since now point 1 is established and governs the value of current until the point becomes unstable. This will occur when the ellipse is tangent at the knee of the reactor curve, at which point the current suddenly increases to a value defined by point 2. Thereafter with further decrease of capacitance, the original curve

is followed. The complete characteristic is similar to those shown in figure 15.

In addition to the current, the reactive voltages may be determined simultaneously by the same process on account of the component nature of the graphical solution. Furthermore, as Rüdenberg[3] has shown, the intersections associated with the upper and lower parts of the ellipse are related to lagging and leading power factor, respectively. The effect of resistance may be observed by varying only the major diameter of the ellipse. If the resistance is sufficiently large, instability is impossible, and a single continuous curve is obtained.

The variation of current as a function of voltage may be studied by observing intersections when both major and minor diameters of the ellipse change while the resistance and capacitance remain constant. With reference to figure 5, it is clear that with rising voltage, the current first increases slowly, then jumps suddenly to a high value (point 2'), and increases continuously thereafter. Upon decreasing the voltage, the current decreases until instability is reached and then falls to a low value. Curves of the same form as those in figure 2 are obtained.

The current as a function of frequency may be adequately described in a relatively simple manner if the reactor voltage is assumed to be directly proportional to fundamental frequency, that is,

$$E_L = \omega F(I) \tag{9}$$

The graphical solution then takes the form

$$F(I) = \pm \frac{1}{\omega}\sqrt{E^2 - (IR)^2} + \frac{I}{\omega^2 C} \tag{10}$$

and the procedure for determining the operating characteristics is analogous to the previous illustrations. In this case, the curve $F(I)$ is constant for all frequencies, whereas both components of the ellipse vary inversely with frequency.

The foregoing examples are indicative of the flexibility of the method of graphical solutions. Although the process of obtaining the circuit characteristics is, from a practical viewpoint, tedious, the presentation gives an unusually clear picture of ferroresonant phenomena. Intrinsically, however, the value of the method lies in the study of critical conditions.

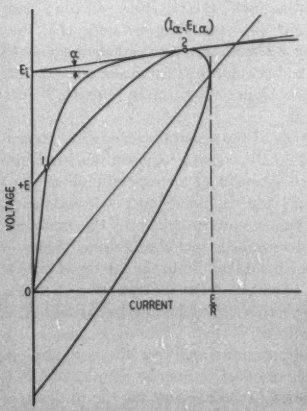

Figure 6. Graphical representation of critical conditions

Critical Quantities

On the basis of the proposed rule, the limit of stability is uniquely defined by common tangency of ellipse and reactor characteristic. In the region of low current (point 1) this condition is possible only in the neighborhood of the knee of the characteristic; hence, the range of critical current values is small. On the other hand, in the region of high current (point 2) the range of critical current values is considerably greater since tangency may occur anywhere along the curve beyond the knee. With these general concepts, the character of critical quantities may be analytically determined. The following treatment deals with point 2, but the results may be applied equally to point 1.

Since, for instability to occur, the ellipse and the reactor must have a common tangent, the intercept of this tangent on the voltage axis E_t (figure 6) may be expressed as

$$E_t = E_{L\alpha} - I_\alpha \left(\frac{dE_L}{dI}\right)_\alpha \tag{11}$$

also

$$\left(\frac{dE_L}{dI}\right)_\alpha \equiv \tan \alpha \tag{12}$$

where $E_{L\alpha}$ and I_α are the critical values of reactor voltage and current at the point of tangency, and tan α, the slope of the tangent.

Employing equation 4, $E_{L\alpha}$ and $(dE_L/dI)_\alpha$ may be evaluated. Thus

$$E_{L\alpha} = + \sqrt{E^2 - (I_\alpha R)^2} + \frac{I_\alpha}{\omega C} \tag{13}$$

$$\left(\frac{dE_L}{dI}\right)_\alpha = \frac{-R^2 I_\alpha}{\sqrt{E^2 - (I_\alpha R)^2}} + \frac{1}{\omega C} \tag{14}$$

Inserting (13) and (14) in (11) and solving for the current, we have

$$I_\alpha = \frac{E}{R}\sqrt{1 - \left(\frac{E}{E_t}\right)^2} \tag{15}$$

The critical capacitance is determined by means of (12), (14), and (15), hence

$$C_\alpha = \frac{1}{\omega\left(\tan \alpha + R\sqrt{\left(\frac{E_t}{E}\right)^2 - 1}\right)} \tag{16}$$

By making use of the expressions for current and capacitance the reactive voltages are obtained.

$$E_{L\alpha} = E\left\{\frac{E}{E_t} + \sqrt{1 - \left(\frac{E}{E_t}\right)^2}\left(\frac{\tan \alpha}{R} + \sqrt{\left(\frac{E_t}{E}\right)^2 - 1}\right)\right\} \tag{17}$$

$$E_{C\alpha} = E\sqrt{1 - \left(\frac{E}{E_t}\right)^2}\left(\frac{\tan \alpha}{R} + \sqrt{\left(\frac{E_t}{E}\right)^2 - 1}\right) \tag{18}$$

Within the limits of assumptions (fundamental frequency), these equations describe the behavior of the critical quantities as functions of the applied voltage, circuit resistance, and characteristic constants of a given iron-core reactor.

Discussion of Equations

A. Region of High Current

In the region of high current characterized by the saturated portion of the reactor characteristic, only the critical conditions for sudden decrease of current exist and are described graphically as the limit of stability at point 2. As this portion of the curve does not include all possible values it is evident that critical quantities related to this point can be defined only within certain limits of applied voltage and circuit resistance. By defining I_0 as the minimum critical current (theoretically, the point at which the tangent leaves the characteristic), the limits of voltage and resistance may be determined by means of equation 15 as follows:

$$I_0 = \frac{E}{R}\sqrt{1 - \left(\frac{E}{E_t}\right)^2} \tag{19}$$

Solving for the voltage,

$$E = \frac{E_t}{\sqrt{2}}\sqrt{1 \pm \sqrt{1 - \left(\frac{2RI_0}{E_t}\right)^2}} \tag{20}$$

for which

$$R \leq \frac{E_t}{2I_0}$$

in order to obtain a real result. Equation 20 gives two values of voltage, and the limiting case occurs for maximum resistance.

$$R_{max} = \frac{E_t}{2I_0} \qquad E_{max} = E_{min} = \frac{E_t}{\sqrt{2}} \tag{21a}$$

$$R \longrightarrow 0 \qquad E_{max} \longrightarrow E_t,\ E_{min} \longrightarrow 0 \tag{21b}$$

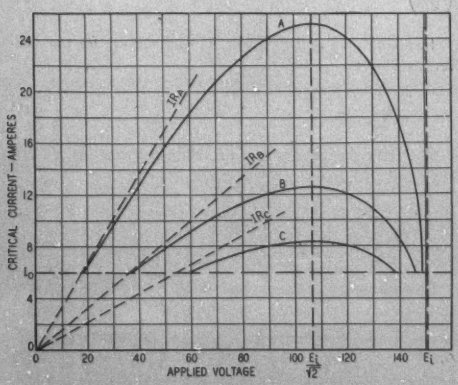

Figure 7. Critical current as a function of voltage. Circuit resistance: A, 3 ohms; B, 6 ohms; C, 9 ohms

Between these limits of applied voltage and resistance instability is possible, and the value of the critical current will be given by (15). It is to be recognized that the above limits are general, and determinate only for the linear portion of the reactor characteristic where E_t is practically constant for a wide range of current values. The maximum critical current is found in the usual manner by differentiation, that is

$$\frac{dI_\alpha}{dE} = \frac{1 - 2\left(\frac{E}{E_t}\right)^2}{R\sqrt{1 - \left(\frac{E}{E_t}\right)^2}} = 0$$

giving

$$E = \frac{E_t}{\sqrt{2}},\ I_{\alpha\,max} = \frac{E_t}{2R} \tag{22}$$

Curves showing the variation of critical current as a function of applied voltage and resistance for the saturated portion of the reactor curve (figure 12), neglecting core losses, are given in figures 7 and 8. These curves give a remarkable insight into the phenomena of ferroresonance and call attention to an interesting fact. Contrary to the results of previous methods, the envelope of critical current is not a straight line coinciding with the (IR) line, but a curve having a maximum and dependent upon the values of voltage and resistance. An examination of the experimental curves (figure 9) given by Rouelle[19] illustrates this point well.

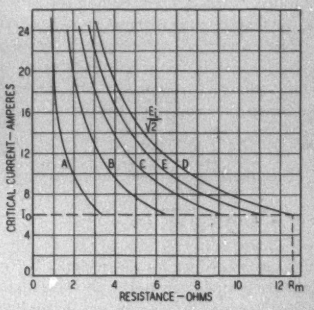

Figure 8. Critical current as a function of resistance applied voltage; A, 20 volts; B, 40 volts; C, 60 volts; D, 106.8 volts; E, 130 volts

From consideration of the equation for critical capacitance, it is evident that the working region in this particular case must be limited in a manner corresponding to the current. Since a single value of capacitance will not suffice, a set of limiting values corresponding to the minimum critical current is determined from the limiting values of voltage and resistance obtained from the curves of critical current. Figures 10 and 11 show the variation of critical capacitance as a function of voltage and resistance; the limiting curves are drawn dotted.

For practical purposes, in applying the equation for critical capacitance, an effective angular frequency (ω^1) is introduced in place of (ω) to account for the presence of

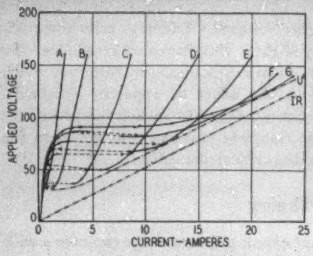

Figure 10 (right). Critical capacitance as a function of voltage. Circuit resistance: A, 3 ohms; B, 6 ohms; C, 9 ohms. Frequency, 60 cycles per second

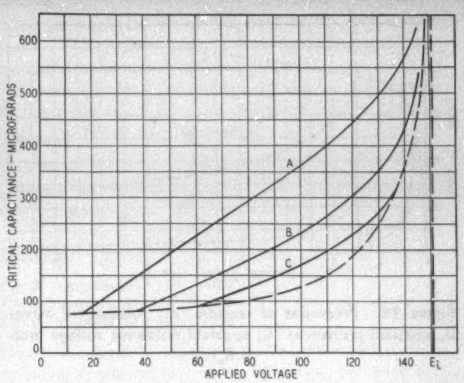

Figure 9. Voltage as a function of current: frequency, 50 cyles per second, resistance 5.2 ohms, capacitance, A, 25 microfarads; B, 40 microfarads; C, 56 microfarads; D, 90 microfarads E, 110 microfarads; F, 126 microfarads; G, 131 microfarads. U′, active component of voltage (experimental results of Rouelle, R. G. E., 1934, page 728)

harmonics. Although the variation of harmonic components of current in ferroresonant circuits is extremely complicated, it has been found that for values of current in the vicinity of breakdown, an effective angular frequency computed from measured values of current, capacitance, and condenser voltage ($\omega^1 = I/E_cC$) is strikingly uniform. In a circuit having a fundamental frequency of 60 cycles per second, the average over a wide range of values of current and capacitance gives

$$\frac{\omega^1}{\omega} = 1.24$$

with a maximum deviation of less than two per cent. For extremely small values of current (point 1), a ratio about nine per cent less is suitable.

Concerning the factors involved in the formulas, the evaluation of circuit resistance is, perhaps, the most important. In addition to the series resistance, consideration must be given to the apparent resistance of the reactor which takes into account the iron losses. This quantity changes both with the degree of saturation and wave form, and it is therefore necessary to have a measure of the variation if accuracy is to be attained.

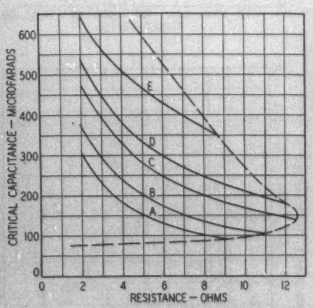

Figure 11. Critical capacitance as a function of circuit resistance. Applied voltage: A, 60 volts; B, 80 volts; C, 106.8 volts; D, 120 volts; E, 140 volts; frequency, 60 cycles per second

As an approximation, it is convenient to determine apparent resistance on the basis of fundamental frequency. The method employed, similar to that of Rouelle,[19] requires power measurements on the reactor with sinusoidal voltage applied. Since under these conditions the average power indicated by the wattmeter is related only to fundamental quantities, the apparent resistance may be defined accordingly as

$$R_A = \frac{P}{I_1^2} \tag{23}$$

where P is the average measured power and I_1, the fundamental component of current at a given value of applied voltage. The variation of apparent resistance and the corresponding fundamental voltage drop (I_1R_A) as a function of effective current are shown in figure 12. The latter quantity is important because in the application of equation 20, total resistance voltage drop required is properly expressed as the sum of the series (external) and the apparent resistance voltage drops. Since the apparent resistance is determined on the basis of fundamental frequency, it follows that the same conditions must be observed for the corresponding voltage drop.

B. Region of Low Current

In the region of low current characterized by the nonlinear portion of reactor characteristic, critical conditions for both sudden increase and decrease of current are theoretically possible. It is necessary therefore, in applying the formulas to determine in what manner the results are related to critical points 1 and 2. In general, it may be inferred from graphical analysis that for point 1, the critical current increases continuously with voltage, whereas, for point 2 a free variation is possible.

Due to the variability of the apparent resistance and the characteristic constants in the nonlinear region, it is advantageous to choose current as an independent variable in order to make a theoretical investigation of critical conditions. For this purpose, equation 20, which gives the voltage as a function of current may be employed. Ob-

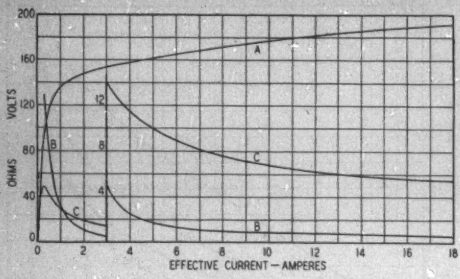

Figure 12. Properties of reactor: A, volt-ampere curve; B, apparent resistance; C, apparent resistance voltage drop (I_1R_a)

viously two values of voltage are possible for every value of current, but only one of these may be associated with point 1 if it exists, the other with point 2. The existence of a critical point 1 depends upon the value of current and resistance in such manner that the voltage given by (20) (positive sign) increases continuously with critical current. This means that only a certain set of critical current values can be defined by this point, and its range, therefore, must be determined by the limiting conditions which are fixed by minimum and maximum values of critical current. With respect to the minimum value the limits of applied voltage and resistance are bound by the same restrictions as in the previous case (21*a*), but are of an indeterminate nature. For the maximum value, these limits are likewise indefinite and can be found only by successive computation; it is the point at which the voltage ceases to increase with critical current (upper limiting value). For critical current values greater than this maximum, both values of voltage given by (20) are clearly associated with the critical point 2. Consequently, the locus of critical current with respect to voltage determined for the nonlinear region of the reactor characteristic includes two distinct portions according to the type of critical condition.

Curves showing the variation of critical current as a function of voltage, taking into account apparent resistance of the reactor (figure 12), are given in figure 13. The solid and dotted portions of the curves are related to critical points 1 and 2, respectively; the dividing line XY is the envelope of limiting values of voltage between which both types of critical conditions are possible. The corresponding curves for critical capacitance are given in figure 14.

The general form of these curves discloses several interesting properties of ferroresonant circuits. Although the abrupt changes in current have been observed to occur alternatively as a pair, the curves give evidence of a possibility of achieving only breakdown of current at low values of voltage beyond the limiting value without the corresponding sudden increase of current. Another interesting feature is that critical current in the region characterized by point 1 increases with resistance, although not appreciably except at higher voltages. Likewise, critical capacitance changes only slightly with increased resistance. In this case, however, there is a nonuniform variation which may be ascribed to the effect of apparent resistance. These families of curves, together with those previously discussed form the complete envelope and illustrate the typical variation of the critical quantities.

Application of Theory

The ferroresonant circuit presents to the engineer a wide variety of possibilities that are useful in relay and control problems. The extent to which these may be utilized is apparent from the circuit properties shown in the preceding curves. In this connection, therefore, it is intended only to suggest what might be done and to give some illustrative examples.

1. Suppose it is desired to design a ferroresonant circuit such that for a given value of series resistance the maximum change in current occurs when the circuit becomes unstable.

If, for example, the case of breakdown of current is considered, the necessary conditions are defined by (22) in which E_t is the only unknown quantity. Assuming that the critical current is related to the saturated portion of the volt-ampere curve of the reactor, the intercept value of

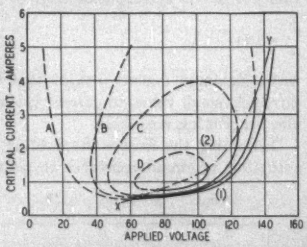

Figure 13. Variation of critical current in region of low current. Series resistance: A, 0 ohms; B, 9 ohms; C, 15 ohms; D, 25 ohms

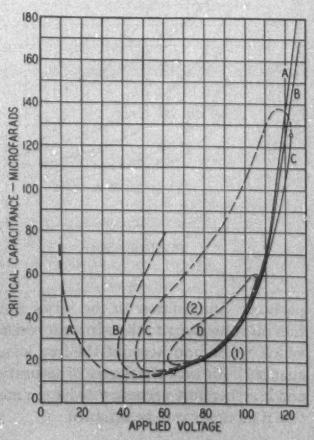

Figure 14. Variation of critical capacitance in region of low current. Series resistance: A, 0 ohms; B, 9 ohms; C, 15 ohms; D, 25 ohms; frequency 60 cyles per second

the tangent is, from figure 12, $E_t = 151$ volts. Thus, if the series resistance, $R_s = 9$ ohms

$$I_{\alpha\,max} = \frac{E_t}{2R} = \frac{151}{18} = 8.38 \text{ amperes}$$

At this current value, the apparent resistance of the reactor is, $R_A = 1$ ohm, which is to be added to the series resistance. Since E_t is about the same as before, the corrected value of current becomes

$$I_{\alpha\,max} = \frac{151}{20} = 7.55 \text{ amperes}$$

and the required applied voltage

$$E = \frac{E_t}{\sqrt{2}} = \frac{151}{\sqrt{2}} = 106.8 \text{ volts}$$

The required circuit capacitance is given by (16) in which $\omega' = 468$ radians per seconds ($f = 60$ cycles per second, $\omega'/\omega = 1.24$); further corresponding to E_t, $\tan \alpha = 2.7$ ohms. Thus,

$$C_\alpha = \frac{1}{468(2.7 + 10)} = 168 \text{ microfarads}$$

If, instead of breakdown, circuit instability with respect to the sudden increase of current were considered, the applied voltage necessary for the maximum change of current is somewhat higher than in the previous case. Evidence of this fact is given in figure 9, curve *e*. To make the computation, therefore, it is only necessary to select a few current values about the knee of the volt-ampere curve that gives by means of (20) a value of voltage about ten per cent higher than in the previous case. This solution also determines the proper characteristic constants to be used in the equation for critical capacitance.

2. Suppose that it is desired to design a ferroresonant circuit that is sensitive to small changes in voltage yet single valued in character (for example, curve *g*, figure 9).

As this condition is related to the upper limiting value of voltage (figure 13), it is necessary to compute several values of voltage by means of (20) corresponding to current values selected above the knee of the volt-ampere curve. The required value is that for which the voltage becomes a maximum with respect to current.

For example, let $R_s = 15$ ohms. Take $I = 1.5$ amperes then from figure 12, $E_t = 127$ volts and $I_1R_A = 22$ volts; $(IR)_{\text{total}} = 22.5 + 22 = 44.5$ volts.

From (20)

$$E = \frac{127}{\sqrt{2}}\sqrt{1 + \sqrt{1 - \left(\frac{89}{127}\right)^2}} = 118.5 \text{ volts}$$

Similarly,

$I = 2$ amperes, $E = 123$ volts
$I = 2.5$ amperes, $E = 123.5$ volts
$I = 3$ amperes, $E = 122.5$ volts

Hence, the required voltage is 123.5 volts and the corresponding constants are: $E_t = 137$ volts, $\tan \alpha = 5.75$ ohms and $R_A = 7$ ohms

therefore,

$$C = \frac{1}{468\left(5.75 + 22\sqrt{\left(\frac{137}{123.5}\right)^2 - 1}\right)} = 131 \text{ microfarads}$$

3. In the general problem, we are concerned with the determination of critical current and capacitance for a given value of applied voltage and series resistance. For this case, the results of experiments on a ferroresonant circuit employing a given reactor are available (figure 15) so that a quantitative check on the theory may be obtained.

For example: $E = 121$ volts, $R_s = 6.65$ ohms (experimental values). Neglecting the apparent resistance of the reactor, a trial calculation is made using the value of intercept voltage, $E_t = 151$ volts, determined from the linear portion of the volt-ampere curve of the reactor. Thus from (15)

$$I_\alpha = \frac{121}{6.65}\sqrt{1 - \left(\frac{121}{151}\right)^2} = 10.9 \text{ amperes}$$

For this value of current, E_t is about the same as assumed above and $R_A = 0.95$, so that the total series resistance becomes 7.60 ohms. The corrected value of critical current is therefore

$$I_\alpha = \frac{121}{7.6}\sqrt{1 - \left(\frac{121}{151}\right)^2} = 9.53 \text{ amperes}$$

From test it is found (see curve *c*, figure 15), $I_\alpha = 8.9$ amperes.

Computing the critical capacitance ($f = 60$ cycles per second, $\omega' = 468$ radians per second, $\tan \alpha = 2.7$ ohms)

$$C_\alpha = \frac{1}{468\left(2.7 + 7.6\sqrt{\left(\frac{151}{121}\right)^2 - 1}\right)} = 255 \text{ microfarads}$$

From test, $C_\alpha = 238$ microfarads

The errors in both cases are seven per cent, approximately.

To find the critical current for the point of sudden increase, it is convenient to employ equation 20 and make a

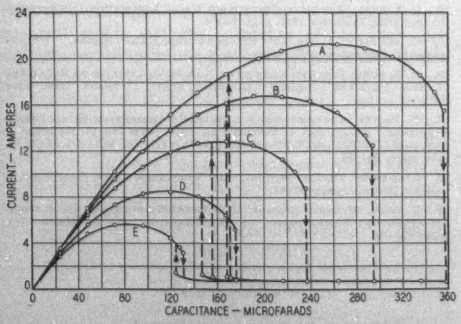

Figure 15. Experimental results; current as a function of capacity. Series resistance: A, 3.88 ohms, B, 5.02 ohms; C, 6.65 ohms; D, 9.9 ohms; E, 14.75 ohms. Applied voltage, 121 volts; frequency 60 cycles per second

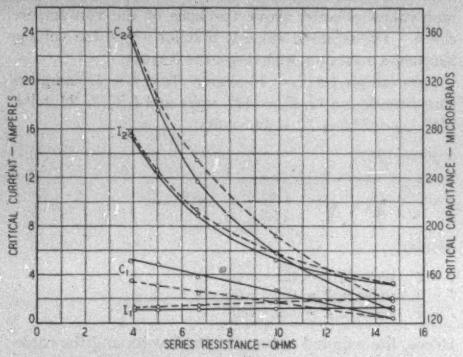

Figure 16. Comparison of measured (solid curves) and computed (dotted curves) values of critical current and capacity as a function of series resistance

few trial substitutions of current values. This is necessary since the characteristic constants change sharply with current about the knee of the volt-ampere curve of the reactor. The solution is given when the calculated voltage is equal to the applied voltage. Since the proper characteristic constants are now available, the calculation of critical capacitance follows directly.

Without going through the computations, reference is made to figure 16 in which a comparison of measured and calculated results is given. The error between these values is confined within reasonable limits and is due primarily to the presence of harmonics, particularly in the reactor voltage, which influence the value of apparent resistance.

Conclusion

The calculation of critical quantities by means of the given formulas is quite simple, although in some instances preliminary computation is required. In any case, the trial substitutions are made with respect to one quantity, and having once determined this quantity, the corresponding critical values of all the other quantities may be readily calculated. This method of obtaining critical quantities is obviously much superior to previous methods which require the determination of families of curves, as in figure 2, from which the desired information is then obtained.

In the study of critical conditions in ferroresonance, this investigation has demonstrated that the characteristic discontinuities of current are not isolated phenomena, but are directly related and occur under parallel circumstances. The principles governing stability and instability have been clearly set forth in the proposed rule for stability, and as a consequence, simple formulas defining critical quantities have been obtained. The rule for stability may also be applied in more complex problems such as the influence of superimposed d-c excitation upon ferroresonance. Critical conditions, as we have seen, are not only dependent upon the properties of the reactor, but also upon the applied voltage and resistance. These facts make for a clear understanding of ferroresonant phenomena and enable the engineer to design circuits to operate under optimum conditions.

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Overvoltages Caused by Unbalanced Short Circuits

Effect of Amortisseur Windings

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Introduction

IN CASE of unbalanced faults on power systems, the voltage on the unfaulted phase or phases may often reach very high values. There may be an overvoltage caused by the short circuit itself and a further overvoltage caused by the clearing of the fault. In the present paper only the first type will be discussed. These unfaulted phase overvoltages may vary widely with the type of fault, the system constants and arrangement, and the kinds of synchronous machines affected. However, in faults not involving ground the presence of overvoltages depends on the fact that the synchronous machines supplying the fault current are not electrically symmetric-rotor machines. Thus, these overvoltages may be largely eliminated or reduced by a properly designed amortisseur winding. Even in case of overvoltages caused by faults involving ground there is a considerable reduction with such an amortisseur winding.

Purely from the standpoint of reducing overvoltages it is evident that such rotor windings are very desirable, and it is advisable to examine carefully each particular case in order to determine how far in the direction of the ideal amortisseur it is economically desirable to go. It is the purpose of this paper to present comparative information on overvoltages caused by one type of fault on a salient-pole synchronous machine with various kinds of amortisseur windings in order to provide one basis for evaluating quantitatively the relative merits of the different types of amortisseur windings. The qualitative effects are of course already known. Mandl[1] has made an extended study of overvoltages caused by single-phase short circuits with terminal capacitance and has shown the existence of resonant points and the possibility of obtaining high voltages on the unfaulted phase of machines with electrically unsymmetrical rotors. Wagner[2] has recently made an experimental study of similar cases. Doherty and Nickle[3] have shown that the magnitude of open-phase voltage during single-phase short circuit of an open-circuited machine is a function principally of the ratio of quadrature-axis reactance to direct-axis reactance, while Park and Skeats[4] have similarly shown how this ratio affects recovery voltage. A later investigation[5] of double line-to-ground faults has given expressions for the open phase voltage for that case. The present paper takes into account more exactly than has hitherto been done the effects of amortisseur windings and of connected terminal capacitance and gives quantitative overvoltage data over a range of machine and system constants.

The practical importance of the study is brought out by lightning arrester and bus failures which could not be reasonably explained except by the high dynamic voltages described in this paper. In one case tests made subsequent to a failure have definitely shown the source of trouble to be these voltages.

In order to obtain the information reported here a detailed study of line-to-line short circuits on a synchronous machine connected to various capacitances and provided with many different designs of amortisseur circuits was made on the differential analyzer[6] at the Moore School of Electrical Engineering of the University of Pennsylvania. By means of the differential analyzer it was possible (1) to take into account most of the significant factors, the effects of which it would be practically impossible to calculate exactly and (2) to vary the machine and line characteristics easily over a wide range, which would be impossible in field tests.

A line-to-line short circuit was studied since this may result in some of the highest overvoltages, and it was not primarily the object to study the effect of various kinds of short circuits but rather the effects of various kinds of amortisseur windings.

Conclusions

As a result of this study the following conclusions have been drawn.

1. High voltages may appear on the unfaulted phase of a synchronous machine with unsymmetrical rotor during line-to-line short circuits.

2. The principal determining factor for the magnitude of overvoltages caused by line-to-line short circuits is the ratio (x_q''/x_d'') of quadrature-axis subtransient reactance to direct-axis subtransient reactance. This ratio is a function of the amortisseur characteristics.

3. The maximum possible overvoltage caused by a line-to-line short circuit on an open circuited machine is given very closely by the formula[3]

$$e_{max} = 2\frac{x_q''}{x_d''} - 1 \qquad (1)$$

4. The overvoltage may be considerably increased over the value of equation 1 by terminal capacitance, the worst condition arising when the capacitive reactance is approximately nine times the negative sequence reactance of the generator. The amount of increase of

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1. For all numbered references, see list at end of paper.

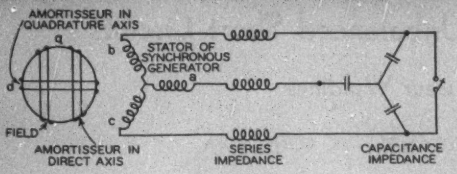


Figure 1

this maximum possible overvoltage depends on the field and armature short circuit time constants, being small when either or both of these quantities are small. For large waterwheel generators the field time constant is ordinarily very large and so may be assumed infinite with little error. On the other hand the terminal capacitance will ordinarily be that of a connected open transmission line and so will be accompanied by a somewhat increased armature circuit resistance which will tend to reduce the armature time constant and consequently the overvoltage.

5. If a salient-pole generator is to be subject to the possibility of connection to an open transmission line of relatively large capacitance or of open circuited operation the ratio x_q''/x_d'' should be kept within limits determined on the basis of permissible overvoltage.

6. The overvoltage will in general be greatly reduced by connection of the salient-pole machine to a power system.

7. The ratio x_q''/x_d'' may be determined by test from single-phase static impedance measurements. The ratio should either be measured at a current equal to the expected rms displaced single-phase short-circuit current or several points taken in order to extrapolate to this current.

Description of System

The system studied is shown in figure 1, the capacitance and series impedance being included to represent approximately the effect of a connected transformer and open transmission line.

The amortisseur circuits of the machine were represented by two windings, one in the field axis of the rotor and one in the quadrature axis, the mutual inductance of the field, direct-axis amortisseur, and direct-axis armature winding being a single quantity. The synchronous machine may therefore be represented by the equivalent circuits of figure 2, in which the machine characteristics are specified by the mutual and leakage reactances of the various windings. The field resistance was neglected, that is, constant flux linkages were assumed in the field circuit, since with the long field time constants of large synchronous generators the change of field flux linkages in the first few cycles after short circuit will be inappreciable and the short circuits will usually not last more than a few cycles. Also the effect of saturation was neglected in so far as it would tend to vary the reactance during the period of short circuit. However it is assumed that the reactances specified apply to saturation conditions corresponding to single-phase short-circuit current. The machine is assumed to conform to the theory of the ideal synchronous machine as defined by Park.[7]

The machine constants were taken as average values for salient-pole (waterwheel) generators, except for the constants of the additional rotor circuits, which were

Table I

Case	x_d''	x_q''	$\frac{x_d''+x_q''}{2}(=x_2)$	x_q''/x_d''	e_1	e_c	$\frac{e_c-1}{e_1-1}$
1	0.439	0.436	0.447	1.04	1.08	1.6	7.5
2	0.456	0.490	0.473	1.07	1.15	2.0	6.66
3	0.478	0.544	0.511	1.14	1.28	2.85	6.6
4	0.489	0.567	0.528	1.16	1.32		
5	0.439	0.516	0.477	1.17	1.35	3.15	6.15
6	0.456	0.553	0.504	1.21	1.42	3.75	6.55
7	0.478	0.616	0.547	1.29	1.58	5.15	7.15
8	0.489	0.650	0.569	1.33	1.66	6.1	7.73
9	0.556	0.900	0.728	1.62	2.24	8.0	5.65

varied over a wide range. The constants (see nomenclature and figure 2 for definition of symbols) used in this study were, in per unit of the machine rating,

$x_l = 0.20$ $\qquad r_{kd} = 0.02$

$x_{ad}' = \dfrac{x_{ad}x_f}{x_{ad}+x_f} = 0.18,\ x_d' = 0.38$ $\qquad r_{kq} = 0.02$ for cases 1–4

$x_{aq} = 0.52,\ x_q = 0.72$ $\qquad r_{kq} = 0.04$ for cases 5–8

Case	x_{kd}	x_{kq}
1	0.09	0.09
2	0.14	0.14
3	0.22	0.24
4	0.29	0.29
5	0.09	0.18
6	0.14	0.26
7	0.22	0.43
8	0.29	0.56
9	∞	∞

Cases 1 to 4 apply to amortisseurs with substantially symmetric leakage reactances, while cases 5 to 8 apply to amortisseurs with quadrature-axis leakage reactance substantially twice those of the direct axis. Case 9 represents a machine with no amortisseur. In all of these cases the series impedance (figure 1) consisted of a reactance of 0.18 per unit and a resistance of 0.05 per unit, except as otherwise indicated. Also in cases 2 and 6 the amortisseur resistances were varied.

The electrical system of figures 1 and 2 may be represented by the set of simultaneous equations of appendix *A*, which were set up on the differential analyzer and solved for the unfaulted phase terminal voltage e_a.

In order fairly to compare the various types of machines, overvoltages were determined for each machine over a range of capacitive reactance, corresponding ap-

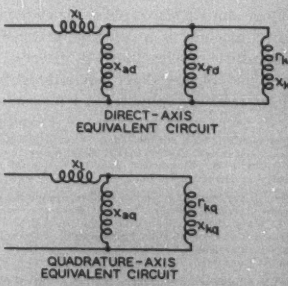


Figure 2

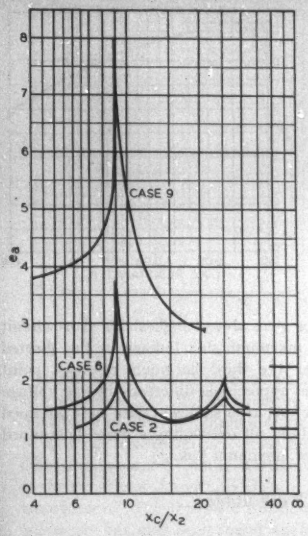


Figure 3. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur winding

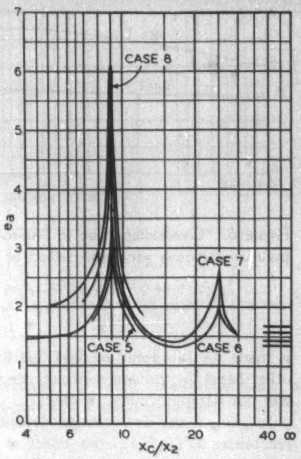


Figure 5. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur reactance

proximately to transmission lines of various voltages and lengths. The range covered varied somewhat but was in general about $3\,x_2 < x_c < 30\,x_2$, where x_2 is the average of the direct- and quadrature-axis subtransient reactances including the external reactance.

Results

Figures 3 to 5 show some of the results obtained. On these curves are recorded the maximum voltage reached in the first four or five cycles following short circuit, as read from the curves of instantaneous voltage versus time plotted by the differential analyzer.

It is seen that as a function of the ratio of line capacitive reactance to average generator subtransient reactance (or negative-sequence reactance) the overvoltage curves have the same characteristic shape for all machines. Voltage peaks are observed at $x_c/x_2 = 9$ and $x_c/x_2 = 25$, which correspond to series resonance of the line capacitance with the negative-sequence reactance for the third and fifth harmonics, respectively.

Figure 3 shows how the addition of the amortisseur winding of case 6 reduces the maximum voltage to about half of the value obtained with no amortisseur winding, and also the further reduction obtainable by the use of the amortisseur of case 2. This latter is particularly noticeable at the resonant point $x_c/x_2 = 9$. The overvoltages obtained when line capacitance is not considered are indicated at the extreme right of the figure. Line capacitance is seen in general to increase the voltages obtained, especially when it is great enough to approach the point of third-harmonic resonance.

Figures 4 and 5 show the effect of variation of the amortisseur leakage reactances. Figure 4 covers the range of amortisseurs with symmetric leakage reactances (cases 1–4), while figure 5 covers the range of unsymmetrical amortisseurs (cases 5–8). As would be expected, the low reactance windings are the most effective. As an indication of the relative effectiveness of the several amortisseur windings table I is given.

The subtransient reactances include the external inductive reactance. The e_0 column contains the maximum open-phase voltages obtained by the formula

$$e_0 = 2\frac{x_q''}{x_d''} - 1 \qquad (1)$$

of Doherty and Nickle,[3] neglecting capacitance and assuming constant amortisseur flux linkage and short circuit at the instant of maximum flux linkage in the shorted phases. The e_c column contains the maximum voltages found by means of the differential analyzer under the worst condition of connected external capacitance $x_c/x_2 = 9$. The last column gives the ratio of maximum excess voltage $(e_c - 1)$ with capacitance to the excess voltage $(e_0 - 1)$ for an open-circuited machine. This ratio is seen to be very nearly a constant quantity since the armature time constant was not varied very much (r_a = constant = 0.05) and the field resistance was constantly zero. Since the maximum voltage e_c occurs several cycles after short circuit it will be somewhat reduced if allowance

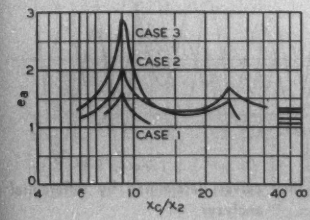


Figure 4. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur reactance

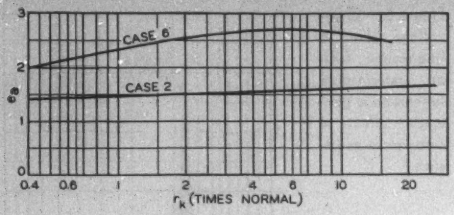


Figure 6. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of amortisseur resistance

Case 6—$x_c/x_2 = 9.9$, $x_q''/x_d'' = 1.21$
Case 2—$x_c/x_2 = 10.6$, $x_q''/x_d'' = 1.07$

is made for the decay of field flux linkage, while on the other hand the voltage e_0, which occurs in the first cycle, will not be appreciably affected.

In general the overvoltages depend principally on the reactances x_d'', x_q'', x_c; the effect of the resistances r_{kd}, r_{kq}, r_a being of secondary importance except in the case of r_a at or near one of the resonant points (particularly at $x_c/x_2 = 9$). Figure 6 shows how at a particular value of line capacitance, and for the machines of cases 2 and 6, the overvoltage is affected by changes of the amortisseur resistances in the ratio of 32 to 1. For the cases investigated, amortisseur resistance has evidently very little effect; there is a slight increase of overvoltage with increasing amortisseur resistance.

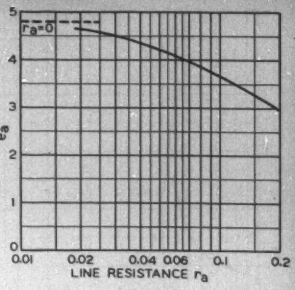
The effect of line resistance r_a in reducing the magnitude of overvoltage is seen in figure 7 for the machine of case 9 with a rather large line capacitance. The case of figure 7 is not a resonant condition, so that line resistance, unless very high, reduces the voltage only about 10 or 20 per cent. At a resonant point the line resistance has much more effect, the voltage in some cases being almost inversely proportional to resistance.

In figure 8 are given some typical voltage-time curves obtained. Inspection of these curves shows that the voltage consists principally of a term of fundamental frequency and one having the frequency $\sqrt{x_c/x_2}$, the latter corresponding to the "average natural frequency" of the series circuit formed by the unfaulted phase. That is, the frequency of the principal natural frequency term can be calculated with good accuracy by neglecting the fact that the machine has an unsymmetrical rotor and using the average of the direct- and quadrature-axis subtransient reactances.

Another point brought out by figure 8 and by the many other voltage curves taken is that with amortisseur windings the voltages in the first few cycles, if the decay of field flux linkages is neglected, are only slightly if at all higher than the values during later cycles after the transients caused by the amortisseur and stator resistances have died away. In fact, in the region where the highest overvoltages are likely to occur, i.e., near $x_c/x_2 = 9$, the voltage requires several cycles to build up to its peak value, which occurs after armature transients have vanished.

Figure 7. Overvoltage due to line-to-line fault on salient-pole synchronous generator—effect of line resistance

Case 9—$x_c/x_2 = 6.86$



The overvoltages were always highest for short circuit at the instant of maximum flux linkage in the shorted phases except near the third harmonic resonant point where there was no appreciable difference in overvoltage with angle. Therefore, after sufficient data were obtained to settle the question, all overvoltages were determined for short circuits at maximum linkage.

Calculation of Overvoltages

Consideration of the form of the voltage curves and of the rather small effect of rotor resistance leads one to the conclusion that for machines with amortisseur windings a good approximation to the voltage may be had by neglecting rotor resistances and also neglecting armature transients. If this is done a relatively simple method of calculation is available (see appendix *B*), the results of which show approximate agreement with those found by the differential analyzer. Figure 9 presents a comparison of calculated and analyzer results for case 6.

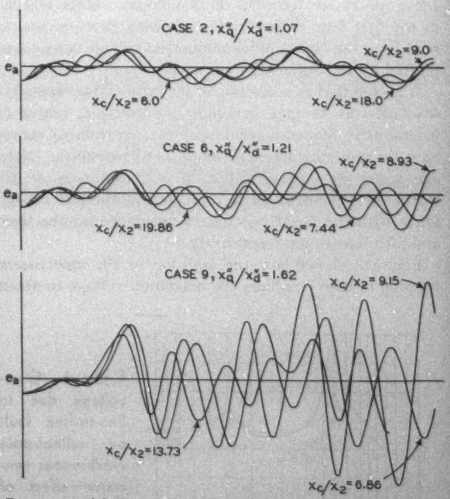


Figure 8. Voltage-time curves determined by differential analyzer

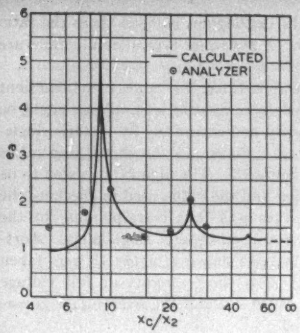


Figure 9. Comparison of calculated steady-state overvoltages with differential analyzer results

Case 6—$x_q''/x_d'' = 1.21$

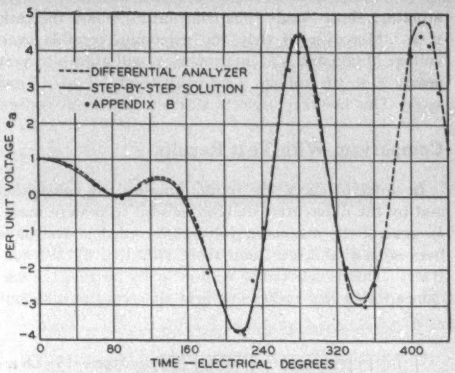


Figure 10. Overvoltage following line-to-line fault on salient-pole synchronous generator

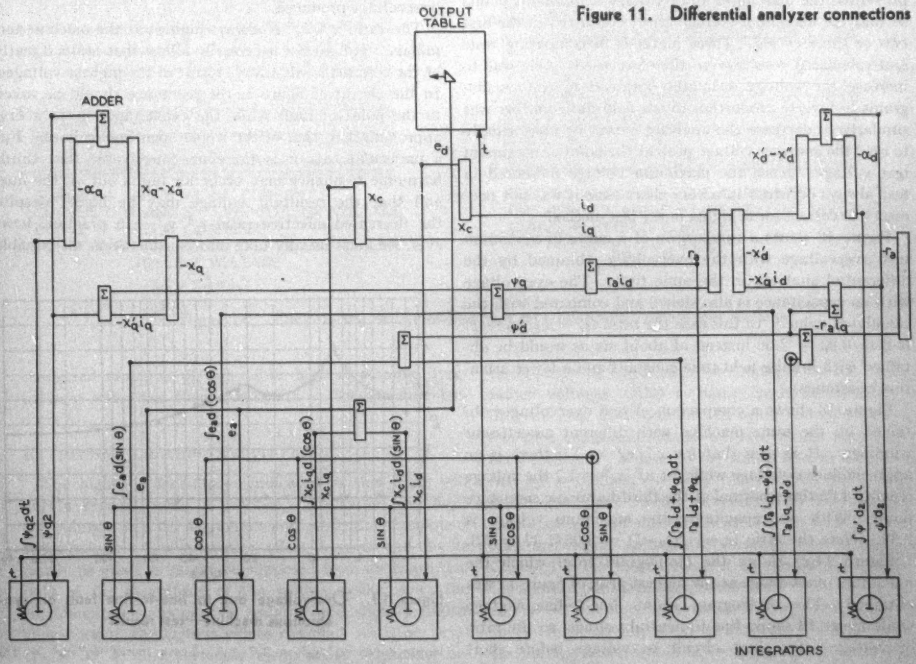
In the case of the synchronous machine with no amortisseur windings (case 9) the armature transients had to be considered in order to obtain a reasonable check. Figure 10 shows a curve of voltage versus time determined by the differential analyzer compared with a step-by-step solution of the equations of appendix B for $r_a = 0$, $x_c = 5$, and no amortisseur. The complete solution including armature transients has also been found analytically as explained in appendix B and points calculated by the formula developed are shown on figure 10.

Equations 8b and 9b of appendix B show that the voltage is a function of the three ratios y/x, r/x, x_c/x. y/x is simply related to the ratio x_q''/x_d'' by the formula,

$$\left(1+\frac{y}{x}\right)\left(1+\frac{x_q''}{x_d''}\right)=2 \qquad (2)$$

while x is very nearly the negative-sequence reactance x_2. The voltage produced is thus a function of x_q''/x_d'', the

Figure 11. Differential analyzer connections



armature short-circuit time constant x_2/r, and the ratio x_c/x_2. Moreover, if only the maximum possible overvoltage obtainable is of interest, x_c/x_2 will always be very nearly 9, so the voltage is a function only of x_q''/x_d'' and x_2/r. This however neglects all rotor decrement factors.

Comparison With Test Results

In order to check the results obtained by calculation and by the differential analyzer several tests were made. In general the maximum voltages recorded in test have been somewhat lower than those indicated by the analyzer. This is believed to be principally because the machines tested had rather low field time constants (about one second open circuit). The rapid decay of field flux prevented the high build-up of voltage at resonant points so that the maximum voltage always occurred in the first two or three cycles. Three methods of comparing tests and calculated results were therefore used. One was to increase the voltage ordinates obtained in test oscillograms in inverse proportion to the field flux, another was similarly to decrease the analyzer curves or more simply to read the analyzer voltage peak at the point of maximum test voltage. Since the maximum voltage measured in test always occurred in a very short time it was not necessary to correct for field flux in the last method.

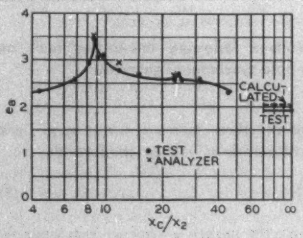


Figure 12. Overvoltage due to line-to-line fault on synchronous machine — comparison of test and analyzer results

$x_q''/x_d'' = 1.52$

Figure 12 shows a comparison of a curve of maximum test overvoltage with the overvoltage obtained by the differential analyzer in the same time. The overvoltage with no capacitance is also shown and compared with the calculated value. In this case the ratio $(e_c - 1)/(e_0 - 1)$ is $2.45/0.92 = 2.66$ instead of about six as would be obtained with infinite field time constant and a lower armature resistance.

Figure 13 shows a comparison of test overvoltages obtained on the same machine with different amortisseur windings. It is seen that for $x_q''/x_d'' = 1.0$ there is no appreciable overvoltage while for $x_q''/x_d'' = 1.7$ the voltage reaches 4.05 times normal at the third-harmonic resonance point. With no capacitance the maximum voltage is 2.32. Here the ratio $(e_c-1)/(e_0-1) = 3.05/1.32 = 2.3$.

Figure 14(*c*) shows the oscillogram from which the maximum overvoltage at the highest peak of figure 13 was obtained. The oscillogram shows line-to-line voltage while figure 13 shows line-to-neutral voltage, so the ratio of voltage after short circuit to voltage before short circuit read from the oscillogram is 0.866 times the ratio plotted in figure 13. A few other typical oscillograms are also given in figure 14.

In the tests it was found that the values of subtransient reactance to be used in computing overvoltage could be determined most easily and accurately by a static single-phase impedance test. Figure 15 shows the test ratios for the machine of figure 13. The high ratio is seen to be affected by saturation and the value used in checking the test overvoltage curves was that corresponding to the calculated offset root-mean-square single-phase short-circuit current. The tests shown in figure 13 were taken at reduced voltage. For short circuits at full voltage the ratio x_q''/x_d'' is about 1.5 and the overvoltage is correspondingly reduced.

Discussion

A. The Ratio x_q''/x_d''

It has been brought out above that overvoltage is principally a function of the ratio x_q''/x_d''. However, except for faults directly at the machine terminals there will be a reactance in series with the machine reactance. Therefore, in these cases a low average subtransient reactance is also desirable since for the same ratio x_q''/x_d'' at the machine terminals the effective ratio at the fault will be lower with lower machine reactance. Thus aside from their effect on the ratio as measured at the machine terminals, amortisseur windings will usually reduce the overvoltage produced.

The ratio x_q''/x_d'' is always highest at the machine terminals. It does not necessarily follow that faults directly at the terminals will always result in the highest voltages. In the circuit of figure 1, the reactance should be taken to the point of fault while the capacitance is, to a first approximation, that of the whole open line or lines. For a particular case it is therefore conceivable that third-harmonic resonance may occur for faults out on the line, and that the resultant voltage may be higher despite the decreased effective ratio x_q''/x_d''. In practice, however, we must usually take into consideration all possible

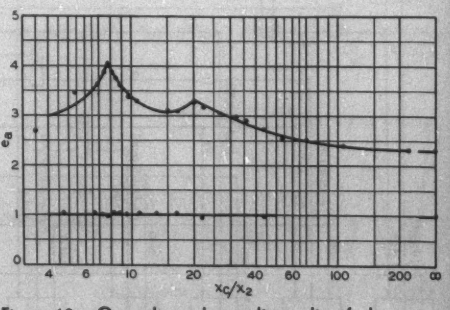


Figure 13. Overvoltage due to line-to-line fault on synchronous machine—test results

Upper curve—$x_q''/x_d'' = 1.7$ Lower curve—$x_q''/x_d'' = 1.0$

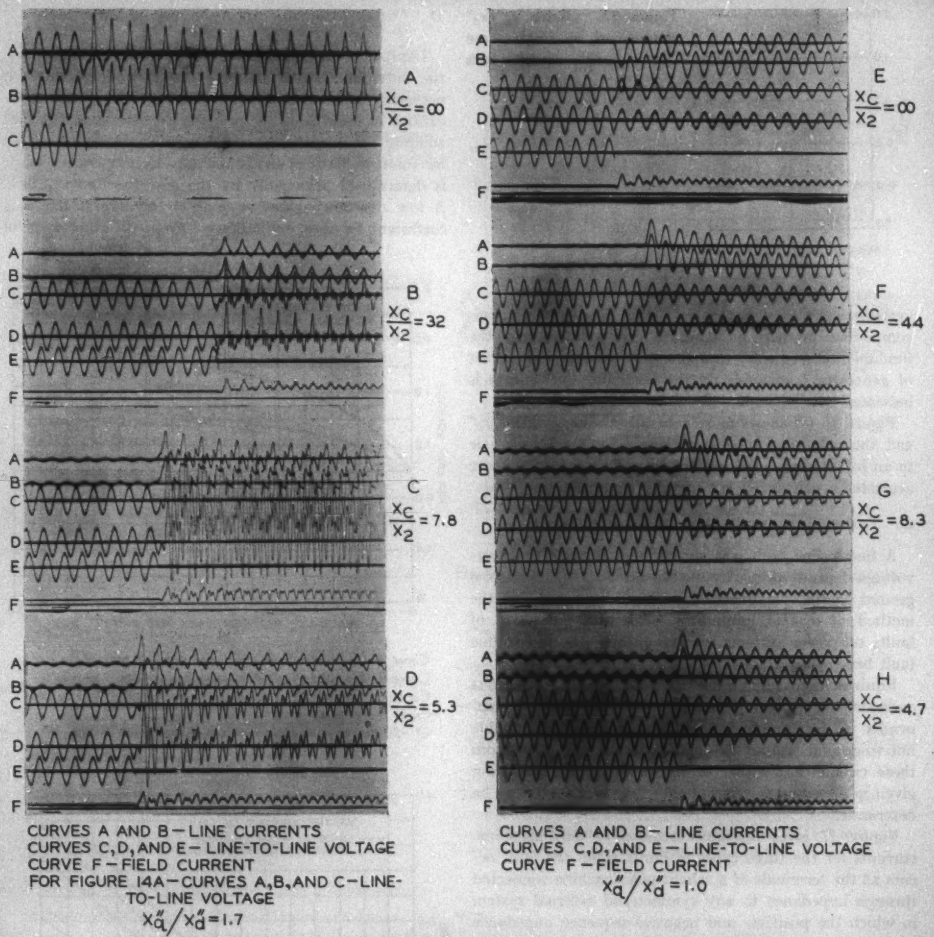


Figure 14. Oscillograms of line-to-line fault on salient-pole synchronous machine

connected amounts of line. The highest possible overvoltages will then occur for faults at the machine terminals.

B. Factors Limiting Overvoltage

The highest overvoltages indicated in this paper will not in general occur in practice. Saturation will limit the voltages to a certain extent and protective equipment will function. The saturation effect however will not be nearly as great as might be supposed from an inspection only of the magnitude of the voltage peaks, since the fundamental component is usually only slightly higher than normal, the highest values recorded consisting principally of a third-harmonic component. Lightning arresters may be expected to be damaged by the high sustained voltages. Also in many cases the machine will be connected to a system. In order to evaluate the effect of a connected system on overvoltage figure 16 has been included. Figure 16 (*a*) shows how in a particular case $x_q'' = 0.90$, $x_d'' = 0.55$, the overvoltage caused by line-to-line short circuit is reduced by the system tie reactance x_e. All the curves are for the condition of no load and equal voltages on machine and infinite bus. Curve *A* is for short circuit at maximum flux linkage in the shorted phases and approaches the value of equation 1 as the tie reactance approaches infinity. Curve *B* is for short circuit at minimum flux linkage. Curve *C* shows the voltage which would be obtained by the conventional

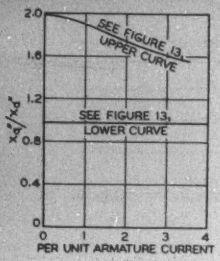


Figure 15. Ratio x_q''/x_d'' determined by single-phase static tests

symmetrical-component calculation. The symmetrical-component method is found to give substantially the fundamental frequency component of voltage. The effect of generator load angle on the maximum overvoltage is indicated by the single point at $x_e = 1.0$.

Figure 16 (*b*) shows more generally the effect of x_q''/x_d'' and the reduction in voltage caused by a reactance tie to an infinite bus. All resistances and capacitances were neglected in calculating the curves of figure 16.

C. Faults Involving Ground

A line-to-line fault was chosen here because the overvoltage depends primarily on the ratio x_q''/x_d'', while for ground faults, the overvoltage is affected also by the method of system grounding. The great majority of faults on power systems involve ground, the line-to-line fault being a less frequent occurrence.

Equivalent circuits for use in determining instantaneous currents and voltages following faults are given in appendix *C* for line-to-ground, line-to-line, and double line-to-ground faults. See figures 18, 19, and 20. From these circuits and either of the methods of calculation given in appendix *B*, overvoltages following faults can be determined.

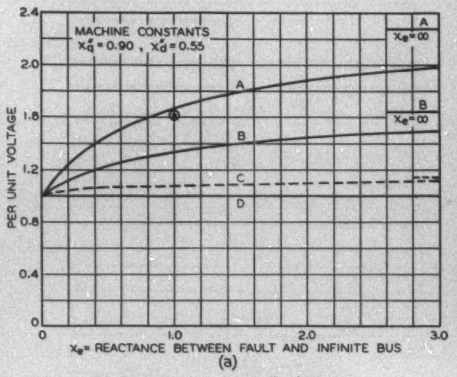
Figure 17 gives resonance regions to third-harmonic currents for the three types of faults when the fault occurs at the terminals of a salient-pole machine connected through impedance to any symmetrical external system in which the positive- and negative-sequence impedance are equal. Resistance is neglected.

Equivalent circuits representing the external system in the positive- and zero-sequence network are shown in figure 17. These circuits consist of a capacitive reactance x_c and an inductive reactance x_c in parallel. In a complex external system, x_{c1}, x_{c0}, x_{1e}, and x_{0e} of the equivalent circuits in general will not be constant for all harmonics.

Figure 17 indicates that with a line-to-ground fault and the assumed ratios of x_{0e}/x_e and x_0/x_1 the capacitance required to cause resonance on a grounded system is high. Even with open lines, a value of x_{c1}/x_1 as low as 5.4 would probably seldom be found in actual systems. For the ungrounded system, the amount of capacitance required for resonance is only about one-fourth to one-fifth as much and the ratio x_{c1}/x_1 lies in a not uncommon region for large systems with long transmission lines.

D. Other Functions of Amortisseur Windings

Limitation or reduction of overvoltage is not, of course, the only function of an amortisseur winding and it is necessary to keep the other aspects of amortisseur applications in mind in order properly to determine the best winding for a particular machine. The damping action for rotor oscillations about a steady-state operating angle is determined principally by the amortisseur resistance. A low resistance gives in general the largest damping coefficient for slow oscillations. From the standpoint of



Curve *A*—No load—fault at maximum flux linkage
Curve *B*—No load—fault at minimum flux linkage
Curve *C*—Symmetrical components—fundamental frequency only
Curve *D*—With $x_q'' = x_d''$
⊙—20-degree load angle—fault at maximum flux linkage

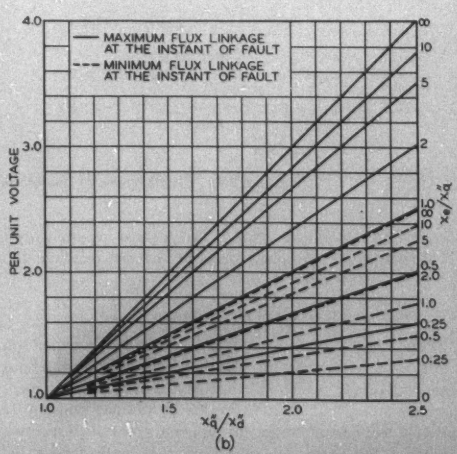


Figure 16. Line-to-line fault on salient-pole generator—maximum voltage at the point of fault—effect of reactance tie to system

stability the damping action of amortisseur windings is beneficial, but in this case a high-reactance winding which will limit the fault current is desirable. An amortisseur winding will also keep the field voltage on open circuit from reaching dangerous values. These functions do not involve the ratio x_q''/x_d''. However, the recovery voltage on clearing faults has been shown[4] to depend on this ratio.

Nomenclature

x_l = armature leakage reactance
x_{ad} = mutual reactance of armature direct-axis winding with field or amortisseur winding
x_f = field leakage reactance
x_{aq} = mutual reactance of armature and amortisseur quadrature-axis windings
x_d' = direct-axis transient reactance
x_q = quadrature-axis synchronous reactance
r_{kd} = direct-axis amortisseur resistance
r_{kq} = quadrature-axis amortisseur resistance
x_{kd} = direct-axis amortisseur leakage reactance
x_{kq} = quadrature-axis amortisseur leakage reactance
i_d = direct-axis armature current
i_q = quadrature-axis armature current
x_d'' = direct-axis subtransient reactance
x_q'' = quadratue-axis subtransient reactance
x_e = external reactance

$y = \dfrac{x_d'' - x_q''}{2}$

$x = \dfrac{x_d'' + x_q''}{2}$

$x_{ad}' = \dfrac{x_{ad}x_f}{x_{ffd}} = x_d' - x_l$

$x_{ffd} = x_{ad} + x_f$ = field self-reactance

x_c = capacitive reactance

$\alpha_d = \dfrac{r_{kd}}{x_{kd} + x_{ad}'}$ = direct-axis amortisseur decrement factor

$\alpha_q = \dfrac{r_{kq}}{x_{kkq}}$ = quadrature-axis amortisseur decrement factor

$x_{kkq} = x_{aq} + x_{kq}$ = quadrature-axis amortisseur self-reactance

e_a = line-to-neutral armature voltage of the unfaulted phase

$\theta = \theta_0 + t$ = angle between direct axis and phase-a axis

ψ_d', ψ_{d2}' = components of direct-axis armature flux linkage

ψ_q, ψ_{q2} = components of quadrature-axis flux linkage

Subscripts 1, 2, 0, α, β refer to positive, negative, and zero sequence, and to α and β components
Subscript e refers to external circuit

e = voltage
i = current
Z = impedance

Appendix A—Equations for Differential Analyzer

The equations as set up on the differential analyzer were:

$$\psi_d' = -x_d'i_d + \psi_{d2}' \tag{1a}$$

$$\psi_{d2}' = (x_d' - x_d'')i_d - \alpha_d\int\psi_{d2}'dt \tag{2a}$$

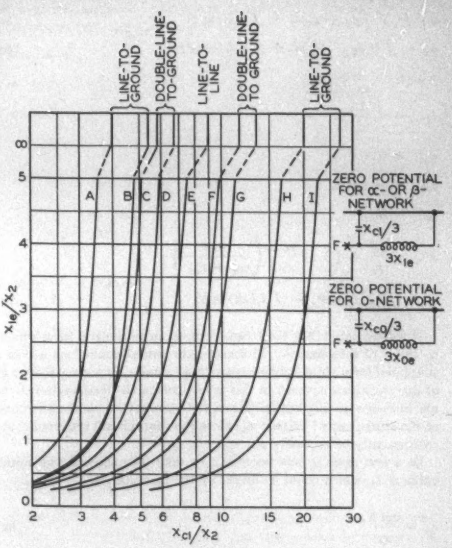


Figure 17. Third-harmonic resonance regions for various types of faults

Curve *A*—Line-to-ground fault, grounded system, $x_0 = x_2/2$, $x_{0e} = x_{1e}$, $C_0 = 0.6\ C_1$
Curve *B*—Line-to-ground fault, grounded system, $x_0 = x_2/2$, $x_{0e} = x_{1e}$, $C_0 = C_1$
Curve *C*—Double line-to-ground fault, grounded system, $x_0 = x_2/2$, $x_{0e} = x_{1e}$, $C_0 = 0.6\ C_1$
Curve *D*—Double line-to-ground fault, grounded system, $x_0 = x_2/2$, $x_{0e} = x_{1e}$, $C_0 = C_1$
Curve *E*—Line-to-line fault
Curve *F*—Double line-to-ground fault, ungrounded system, $C_0 = 0.6\ C_1$
Curve *G*—Double line-to-ground fault, ungrounded system, $C_0 = C_1$
Curve *H*—Line-to-ground fault, ungrounded system, $C_0 = 0.6\ C_1$
Curve *I*—Line-to-ground fault, ungrounded system, $C_0 = C_1$

where

$\alpha_d = \dfrac{r_{kd}}{x_{kd} + x_{ad}'}$

$x_{ad}' = \dfrac{x_{ad}x_{fd}}{x_{ffd}}$

$\psi_{d20}' = -\left(\dfrac{x_d' - x_d''}{x_c}\right) - \left(1 - \dfrac{x_d'}{x_c}\right)\left(\dfrac{x_{ad}'}{x_{kd} + x_{ad}'}\right)$

= initial value of ψ_{d2}'

$$\psi_q = -x_qi_q + \psi_{q2} \tag{3a}$$

$$\psi_{q2} = (x_q - x_q'')i_q - \alpha_q\int\psi_{q2}dt \tag{4a}$$

where

$\alpha_q = \dfrac{r_{kq}}{x_{kkq}}$

$\psi_{q20} = 0$

$$\psi_d' = \int (r_a i_d + \psi_q) dt + \int e_d d(\sin\theta) \quad (5a)$$

$$\psi_q = \int (r_a i_q - \psi_d') dt + \int e_d d(\cos\theta) \quad (6a)$$

where

$$i_{d0} = -\frac{1}{x_c}$$

$$\psi_{q0} = 0$$

$$e_{q0} = -\sin\theta_0$$

$$i_{q0} = 0$$

$$\psi'_{d0} = \frac{x_d''}{x_c} + \left(1 - \frac{x_d'}{x_c}\right)\left(\frac{x_{kd}}{x_{kd} + x_{ad}'}\right)$$

$$e_a = \int x_c i_d d(\sin\theta) + \int x_c i_q d(\cos\theta) \quad (7a)$$

It will be noted that these equations are in an integral form similar to those of reference 8. Moreover, the initial conditions are in a simplified form valid only for reasonably small r_a, since for the range of line resistance covered in this investigation the load angle δ of the machine was usually negligible and the terminal (i.e., at the terminals of the capacitance) voltage e_a before the short circuit occurred could consequently be expressed as: $e_{q0} = 1$, $e_{d0} = 0$.

In a few cases it was necessary to take into account the initial value of i_q, which could be found by the formula

$$i_{q0} = \frac{\sin\delta}{x_c} \quad (8a)$$

where[9]

$$\tan\delta = \frac{r_a}{x_c - x_q}$$

Equations 1*a* to 7*a* may be derived from Park's[10] synchronous-machine equations, in exactly the same manner as were the equations of reference 8, and so need not be derived here. It should only be pointed out that in equation 5*a* the expression $e_d d(\sin\theta) = e_d \cos\theta\, dt = e_d\, dt$, and similarly for the similar expressions of equations 6*a* and 7*a*. This substitution was made in order to obtain the most desirable analyzer setup.

With the equations expressed as above, eight integrators are seen to be required. In addition, the two remaining integrators were used to generate the required sinusoidal functions[11] $\sin\theta$, $\cos\theta$, so the setup was entirely self contained and required no operators. Figure 11 shows a schematic diagram of the analyzer connections.

Appendix B—Calculation of Overvoltages

The equations of an ideal synchronous machine with any static terminal impedance under the conditions that (1) all rotor resistances are negligibly small, (2) the external circuit parameters are constants, (3) the external circuit is symmetric about phase *a* of the synchronous machine, and (4) the rotor speed is constant, are most simply and conveniently expressed for the present purpose as:

$$\left.\begin{aligned} e_\alpha &= -[p(x + y\cos 2\theta) + r]\, i_\alpha - py \sin 2\theta\, i_\beta = Z_\alpha(p) i_{\alpha e} \\ e_\beta &= -py \sin 2\theta\, i_\alpha - [p(x - y\cos 2\theta) + r]\, i_\beta = Z_\beta(p) i_{\beta e} \\ e_0 &= -[px_0 + r]\, i_0 = Z_0(p) i_{0e} \end{aligned}\right\} \quad (1b)$$

where

$$\left.\begin{aligned} x &= \frac{1}{2}(x_d'' + x_q'') \\ y &= \frac{1}{2}(x_d'' - x_q'') \end{aligned}\right\} \quad (2b)$$

r = armature circuit resistance

$Z_\alpha(p)$, $Z_\beta(p)$, $Z_0(p)$ = operational impedances of the external connected circuit to the α, β, and 0 components of current, respectively

i_α, i_β, i_0 are components of the stator currents defined in terms of the phase currents by the equations:

$$\left.\begin{aligned} i_\alpha &= \frac{2}{3} i_a - \frac{1}{3} i_b - \frac{1}{3} i_c \\ i_\beta &= \frac{1}{\sqrt{3}} i_b - \frac{1}{\sqrt{3}} i_c \\ i_0 &= \frac{1}{3} i_a + \frac{1}{3} i_b + \frac{1}{3} i_c \end{aligned}\right\} \quad (3b)$$

$i_{\alpha e}$, $i_{\beta e}$, i_{0e} are the similar currents flowing in the external circuit. The currents i_α, i_β may also be expressed in terms of the direct- and quadrature- axis components of current by the equations:

$$\left.\begin{aligned} i_\alpha &= i_d \cos\theta - i_q \sin\theta \\ i_\beta &= i_d \sin\theta + i_q \cos\theta \end{aligned}\right\} \quad (4b)$$

i_α is the component of armature current which produces a field in the axis of phase *a* of the synchronous machine and may be regarded as a current which flows through phase *a* and splits into two equal parts which flow through phases *b* and *c* in parallel. i_β is the component of armature current which produces a field in the common axis of phases *b* and *c* and may be regarded as a current flowing only through phases *b* and *c* in series. e_α, e_β, e_0 are components of armature voltage defined by voltage equations similar to (3*b*) and (4*b*). In the special case of a machine without an amortisseur winding the subtransient reactances x_d'', x_q'' are replaced by x_d', x_q, respectively.

Equations 1*b* are most easily derived from the equations of a synchronous machine (with no external impedance) in terms of direct- and quadrature-axis quantities.[10] These are, for zero rotor resistances,

$$\left.\begin{aligned} e_d &= -(p x_d'' + r) i_d + x_q'' i_q \\ e_q &= -x_d'' i_d - (p x_q'' + r) i_q \end{aligned}\right\} \quad (5b)$$

Now if equations 4*b* and the similar voltage equations are applied there are equations 1*b* except for the $Z_\alpha(p)$, $Z_\beta(p)$ terms. It is now evident from a consideration of the circuit and the physical interpretations of i_α, i_β, $i_{\alpha e}$, $i_{\beta e}$, e_α, e_β that if a static network is connected to the machine terminals the complete equations 1*b* are obtained. Moreover, if the network is completely symmetric, there is:

$$Z_\alpha(p) = Z_\beta(p) = Z_1(p) = Z_2(p) \quad (6b)$$

where $Z_1(p)$, $Z_2(p)$ are the positive- and negative-sequence operational impedances of the external circuit.

For a line-to-line fault, as shown in figure 1, there is

$$Z_\alpha(p) = \frac{x_c}{p} \quad (7b)$$

and there are no zero-sequence currents or voltages.

Before the fault let

$$e_a = -\sin(\theta_0 - \phi + t)$$

where ϕ is the load angle. Then, from (3*b*)

$$e_\alpha = -\sin(\theta_0 - \phi + t)$$

$$e_\beta = \cos(\theta_0 - \phi + t)$$

The fault is equivalent to the application of a voltage at the terminals of the machine equal and opposite to e_β. Thus when the voltage $e_\beta = -\cos(\theta_0 + t)$ is applied to equations 1*b*, we obtain the components of current caused by the fault. Further the terminal voltage e_α is given by

$$e_\alpha = \frac{x_c}{p} i_\alpha \quad (8b)$$

and the total resultant is obtained by adding e_a to the voltage existing before short circuit. If the speed is constant the current may be obtained as follows.

Equations 1*b* may be written

$$\left.\begin{aligned}[p(1 + y' \cos 2\theta) + r' + Z_\alpha'(p)]\, x i_\alpha + (py' \sin 2\theta)\, x i_\beta &= 0 \\ (py' \sin 2\theta)\, x i_\alpha + [p(1 - y' \cos 2\theta) + r']\, x i_\beta &= \cos(\theta_0 + t)\end{aligned}\right\} \quad (9b)$$

where

$$y' = \frac{y}{x}, \quad r' = \frac{r}{x}, \quad Z' = \frac{Z}{x}$$

It is difficult to obtain a simple finite operational solution to equations 9*b* because of the presence of the periodic time functions in the current coefficients. However a solution may easily be found by expanding the currents in powers of the troublesome coefficient y' about $y' = 0$. We then have

$$\left.\begin{aligned}i_\alpha &= i_{\alpha 0} + i_{\alpha 0}' y' + \frac{i_{\alpha 0}''}{2!} y'^2 + \cdots\cdots \\ i_\beta &= i_{\beta 0} + i_{\beta 0}' y' + \frac{i_{\beta 0}''}{2!} y'^2 + \cdots\cdots\end{aligned}\right\} \quad (10b)$$

where the primes on the currents indicate differentiation with respect to y' and the subscripts zero indicate evaluation at $y' = 0$.

To obtain $i_{\alpha 0}$, $i_{\beta 0}$ we have merely to let $y' = 0$ in equations 9*b* and then to solve the resulting two independent equations operationally. Next, to obtain $i_{\alpha 0}'$, $i_{\beta 0}'$ we must (1) differentiate (9*b*) with respect to y', (2) let $y' = 0$, (3) substitute for $i_{\alpha 0}$, $i_{\beta 0}$ their values as previously found, (4) obtain the operational solution to the resulting equation. To obtain $i_{\alpha 0}''$, $i_{\beta 0}''$ we proceed in exactly the same way by differentiating again and utilizing the previously found values of $i_{\alpha 0}'$, $i_{\beta 0}'$. For the general coefficients $i_{\alpha 0}^{n'}$, $i_{\beta 0}^{n'}$ of (10*b*) there are the equations,

$$\left.\begin{aligned}[p + r' + Z_\alpha'(p)]\, i_{\alpha 0}^{(n-1)'} &= \\ &\quad - np\,[(\cos 2\theta)\, i_{\alpha 0}^{(n-1)'} + (\sin 2\theta)\, i_{\beta 0}^{(n-1)'}] \\ [p + r']\, i_{\beta 0}^{n'} &= - np\,[(\sin 2\theta)\, i_{\alpha 0}^{(n-1)'} - (\cos 2\theta)\, i_{\beta 0}^{(n-1)'}]\end{aligned}\right\} \quad (11b)$$

The currents, and consequently the terminal voltage by equation 8*b*, are now determined as infinite series of transient and steady-state terms which, however, converge rapidly because in the usual case y' is much smaller than unity. Figure 10 shows for a particular case a comparison of voltage calculated by the formulas developed above with a curve taken on the differential analyzer and with a step-by-step solution of equations 1*b*. Only the first two terms of (10*b*) were considered in calculating the points of figure 10.

If only the steady-state (as far as armature transients are concerned) voltage is desired the equations are very much simplified since then the currents and voltages appear only as a series of odd-harmonic terms and the operational impedances of equations 1*b* and 11*b* may be replaced by steady-state impedances at the proper frequency. Figure 9 shows a comparison of maximum overvoltages calculated by this simplified method with the overvoltages obtained by the differential analyzer.

A second method of procedure in solving equations 1*b* is to assume that currents and voltages of fundamental frequency can be determined with sufficient accuracy by the method of symmetrical components. It can be applied to systems of any degree of complexity. Since symmetrical components are in general use, the procedure in determining instantaneous currents and voltages following faults will be given in terms of symmetrical components, the α- and β-components being used only to pass from direct and quadrature components to symmetrical components. An advantage of using α- and β-components over positive- and negative-sequence components, is that the relations among the α and β currents and voltages may be expressed by real coefficients.

The following equations give the relations between the positive- and negative-sequence components of currents, voltages, and impedances and the α- and β-components.

$$\left.\begin{aligned}i_\alpha &= i_{a1} + i_{a2} \\ i_\beta &= -j(i_{a1} - i_{a2}) \\ e_\alpha &= e_{a1} + e_{a2} \\ e_\beta &= -j(e_{a1} - e_{a2}) \\ i_{a1} &= \frac{1}{2}(i_\alpha + j i_\beta) \\ i_{a2} &= \frac{1}{2}(i_\alpha - j i_\beta) \\ e_{a1} &= \frac{1}{2}(e_\alpha + j e_\beta) \\ e_{a2} &= \frac{1}{2}(e_\alpha - j e_\beta) \\ Z_\beta &= \frac{1}{2}(Z_1 + Z_2) \\ Z_\alpha &= 2\frac{Z_1 Z_2}{Z_1 + Z_2} \cong \frac{1}{2}(Z_1 + Z_2)\end{aligned}\right\} \quad (12b)$$

Reference Vector

In the method of symmetrical components, sinusoidal voltages and currents of fundamental frequency are represented by vectors referred to some particular vector as reference. Thus, if the voltage e_a of phase a at some specified point leads the reference vector by an angle α, it is written

$$e_a = |e_a| \underline{/\alpha} = E_a \underline{/\alpha}$$

To express e_a as a function of time, let the fundamental frequency component of e_a be written

$$e_{1a} = -E_{1a} \sin(\theta + \alpha_1) = E_{1a} \underline{/\theta + \alpha_1}$$

and the nth harmonic component of e_a

$$e_{na} = -E_{na} \sin(n\theta + \alpha_n) = E_{na} \underline{/n\theta + \alpha_n}$$

where θ is the position of the axis of the rotor of a specified machine in electrical degrees measured from the axis of phase a.

The following expressions for instantaneous values of currents and voltages of any frequency will be used interchangeably,

$$-V \sin(n\theta \pm \alpha) = V \underline{/n\theta \pm \alpha}$$

$$V \cos(n\theta \pm \alpha) = -jV \underline{/n\theta \pm \alpha} = V \underline{/n\theta \pm \alpha - 90°}$$

$$\pm jV \sin(n\theta + \alpha) = V \sin(n\theta + \alpha \pm 90°) = \pm V \cos(n\theta + \alpha)$$

$$\pm jV \cos(n\theta + \alpha) = V \cos(n\theta + \alpha \pm 90°) = \mp V \sin(n\theta + \alpha)$$

Let

$$\left.\begin{aligned}i_{na1} &= \text{positive-sequence } n\text{th harmonic current} \\ &= -jI_{na1} \underline{/n\theta + \alpha_{n1}} = I_{na1} \cos(n\theta + \alpha_{n1}) \\ i_{na2} &= \text{negative sequence } n\text{th harmonic current} \\ &= -jI_{na2} \underline{/n\theta + \alpha_{n2}} = I_{na2} \cos(n\theta + \alpha_{n2})\end{aligned}\right\} \quad (13b)$$

where α_{n1} and α_{n2} are determined by the system impedances, type of fault, and load angle.

Generated Voltages

When $x_q'' = x_d''$, currents and voltages following faults will in the general case have a fundamental-frequency term, one or more natural-frequency terms, and a d-c term. These can be determined by

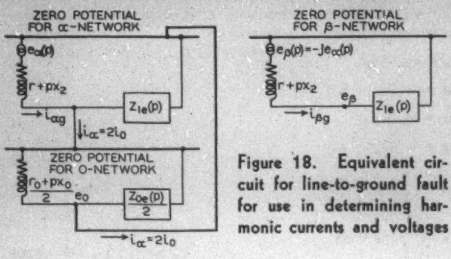


Figure 18. Equivalent circuit for line-to-ground fault for use in determining harmonic currents and voltages

applying a voltage at the fault equal and opposite to that which existed there before the fault and adding resulting changes in currents and voltages to initial values. When $x_q'' \neq x_d''$, additional voltages are generated. From (1*b*) the voltages generated by sinusoidal currents i_α and i_β of any frequency are

$$\left.\begin{aligned} e_\alpha &= -py(\cos 2\theta i_\alpha + \sin 2\theta i_\beta) \\ e_\beta &= -py(\sin 2\theta i_\alpha - \cos 2\theta i_\beta) \end{aligned}\right\} \quad (14b)$$

Replacing i_α and i_β in (14*b*) by their positive- and negative-sequence values from (12*b*) and substituting for them the expressions in (13*b*), positive- and negative-sequence voltages generated in a given machine can be determined as follows:

$$\left.\begin{aligned} e_\alpha &= -py[I_{n\alpha 1}\{\cos 2\theta \cos(n\theta + \alpha_{n1}) + \sin 2\theta \sin(n\theta + \alpha_{n1})\} + I_{n\alpha 2}\{\cos 2\theta \cos(n\theta + \alpha_{n2}) - \sin 2\theta \sin(n\theta + \alpha_{n2})\}] \\ &= -py[I_{n\alpha 1}\cos\{(n-2)\theta + \alpha_{n1}\} + I_{n\alpha 2}\cos\{(n+2)\theta + \alpha_{n2}\}] \\ &= (n-2)yI_{n\alpha 1}\sin\{(n-2)\theta + \alpha_{n1}\} + (n+2)yI_{n\alpha 2}\sin\{(n+2)\theta + \alpha_{n2}\} \\ e_\beta &= -py[I_{n\alpha 1}\{\sin 2\theta \cos(n\theta + \alpha_{n1}) - \cos 2\theta \sin(n\theta + \alpha_{n1})\} + I_{n\alpha 2}\{\sin 2\theta \cos(n\theta + \alpha_{n2}) + \cos 2\theta \sin(n\theta + \alpha_{n2})\}] \\ &= -py[-I_{n\alpha 1}\sin\{(n-2)\theta + \alpha_{n1}\} + I_{n\alpha 2}\sin\{(n+2)\theta + \alpha_{n2}\}] \\ &= (n-2)yI_{n\alpha 1}\cos\{(n-2)\theta + \alpha_{n1}\} - (n+2)yI_{n\alpha 2}\cos\{(n+2)\theta + \alpha_{n2}\} \end{aligned}\right\} \quad (15b)$$

If $n \geq 2$

$$je_\beta = -(n-2)yI_{n\alpha 1}\sin\{(n-2)\theta + \alpha_{n1}\} + (n+2)y\,I_{n\alpha 2}\sin\{(n+2)\theta + \alpha_{n2}\} \quad (16b)$$

$$e_{\alpha 1} = (n+2)yI_{n\alpha 2}\sin\{(n+2)\theta + \alpha_{n2}\} = -(n+2)y\,I_{n\alpha 1}/\underline{(n+2)\theta + \alpha_{n2}} = (n+2)\,y/\underline{2\theta - 90°}\; i_{n\alpha 2} \quad (17b)$$

$$e_{a2} = (n-2)yI_{n\alpha 1}\sin\{(n-2)\theta + \alpha_{n1}\} = -(n-2)yI_{n\alpha 1}/\underline{(n-2)\theta + \alpha_{n1}} = (n-2)y/\underline{-2\theta - 90°}\; i_{n\alpha 1} \quad (18b)$$

If $n = 1$

$$\left.\begin{aligned} e_{a1} &= yI_{n\alpha 1}\sin(\theta - \alpha_{n1}) \\ &= -yI_{1\alpha 1}/\underline{\theta - \alpha_{11}} = y/\underline{-2\alpha_{11} - 90°}\; i_{1\alpha 1} \\ e_{a2} &= 0 \end{aligned}\right\} \quad (19b)$$

From (17*b*), (18*b*), (19*b*), positive- and negative-sequence voltages generated by harmonic current without decrements can be determined.

Steady State

Since zero rotor resistance has been assumed in the direct and quadrature axes, there will be no field decrements and fundamental-frequency and odd-harmonic terms of currents and voltages will have no decrements. Natural-frequency and even harmonic terms will disappear in the steady state.

Table II gives the positive- and negative-sequence odd-harmonic voltages generated by positive- and negative-sequence odd-harmonic currents.

Procedure in Determining Steady-State Values of Currents and Voltages Following Faults

Assuming zero resistance in the field for machines without amortisseur windings and also in the amortisseur for those with amortisseur windings, the procedure for determining currents and voltages in the steady state following faults is as follows:

1. Calculate currents and voltages of fundamental frequency in the system by means of symmetrical components. Since it has been assumed that fundamental-frequency currents and voltages are determined with sufficient accuracy by this method, voltages of fundamental frequency generated in machines in which $x_d'' \neq x_q''$ will be neglected.

2. From the negative-sequence current flowing in machines in which $x_d'' \neq x_q''$, determine the third-harmonic positive-sequence generated voltages from table II.

3. From third-harmonic positive-sequence generated voltages determine by symmetrical components the third-harmonic voltages and currents in the systems, assuming positive and negative impedance of the synchronous machines to third-harmonic currents to be $3x_2$. x_2 may differ slightly from the fundamental-frequency value.

4. From the negative sequence third-harmonic currents flowing in machines in which $x_d'' \neq x_q''$, determine from table II the fifth-harmonic positive-sequence generated voltages.

Proceeding in this manner, odd-harmonic currents and voltages can be determined at any point of the system.

It is also possible to calculate the transient voltage caused by odd harmonic currents and, by using the natural frequency and even harmonic currents in equations (14*b*) to calculate the generated transient voltages and from them in turn the resulting terminal overvoltage.

Appendix C—Equivalent Circuits for Various Types of Faults

Let i_a, i_b, and i_c be phase currents flowing into the fault; $Z_0(p)$ the zero-sequence impedance viewed from the fault; e_a, e_b, and e_c the phase-to-ground voltages at the fault, and e_α, e_β, and e_0 their α-, β-, and 0-components, respectively.

Line-to-Ground Fault (Phase a)

Conditions at the fault are:

$i_b = i_c = 0$; $e_a = 0$

From (3*b*)

$i_\beta = 0$; $i_\alpha = 2i_0$; $e_\alpha = -e_0$

Table II. Positive- and Negative-Sequence* Odd-Harmonic Generated Voltages

Positive-Sequence Odd-Harmonic Voltages Generated in Machines by Negative-Sequence Currents

$$e_{1\alpha 1} = 3yI_{1\alpha 1}\sin(3\theta + \alpha_{12}) = -3yI_{1\alpha 1}/3\theta + \alpha_{12} = 3y/2\theta - 90°\; i_{1\alpha 1}$$
$$e_{5\alpha 1} = 5yI_{5\alpha 1}\sin(5\theta + \alpha_{52}) = -5yI_{5\alpha 1}/5\theta + \alpha_{52} = 5y/2\theta - 90°\; i_{5\alpha 1}$$
$$e_{7\alpha 1} = 7yI_{5\alpha 1}\sin(7\theta + \alpha_{72}) = -7yI_{5\alpha 1}/7\theta + \alpha_{72} = 7y/2\theta - 90°\; i_{5\alpha 1}$$
$$e_{9\alpha 1} = 9yI_{7\alpha 1}\sin(9\theta + \alpha_{72}) = -9yI_{7\alpha 1}/9\theta + \alpha_{72} = 9y/2\theta - 90°\; i_{7\alpha 1}$$

Negative-Sequence Odd-Harmonic Voltages Generated in Machines by Positive Sequence Currents

$$e_{1\alpha 2} = yI_{1\alpha 1}\sin(\theta + \alpha_{11}) = -yI_{1\alpha 1}/\theta + \alpha_{11} = y/-2\theta - 90°\; i_{1\alpha 1}$$
$$e_{3\alpha 2} = 3yI_{3\alpha 1}\sin(3\theta + \alpha_{31}) = -3yI_{3\alpha 1}/3\theta + \alpha_{31} = 3y/-2\theta - 90°\; i_{3\alpha 1}$$
$$e_{7\alpha 2} = 5yI_{7\alpha 1}\sin(5\theta + \alpha_{71}) = -5yI_{7\alpha 1}/5\theta + \alpha_{71} = 5y/-2\theta - 90°\; i_{7\alpha 1}$$
$$e_{7\alpha 2} = 7yI_{9\alpha 1}\sin(7\theta + \alpha_{91}) = -7yI_{9\alpha 1}/7\theta + \alpha_{91} = 7y/-2\theta - 90°\; i_{9\alpha 1}$$

*α and β voltages when required can be obtained from table II and (12*b*).

It follows that

$$-e_b = Z_0(p)i_0 = \frac{Z_0(p)}{2}\, i_\alpha = e_\alpha \qquad (1c)$$

From (1c) the equivalent circuit to replace the fault in the α-network is $Z_0(p)/2$. When $x_d'' = x_q''$, the β-network is not involved, e_β is not changed by the fault, and e_α and e_0 have only fundamental- and natural-frequency terms. In machines in which $x_d'' \neq x_q''$, fundamental-, harmonic- and other frequency voltages are generated (see appendix B) which affect e_α, e_β, and e_0.

At the fault, since $e_a = -e_b$, e_a, e_b, and e_c are:

$$\left.\begin{aligned} e_a &= e_\alpha + e_0 = 0 \\ e_b &= -\frac{1}{2}e_\alpha + e_0 - \frac{\sqrt{3}}{2}e_\beta = \frac{3}{2}e_0 - \\ &\qquad \frac{\sqrt{3}}{2}e_\beta = -\frac{3}{2}e_\alpha - \frac{\sqrt{3}}{2}e_\beta \\ e_c &= -\frac{1}{2}e_\alpha + e_0 + \frac{\sqrt{3}}{2}e_\beta = \frac{3}{2}e_0 + \\ &\qquad \frac{\sqrt{3}}{2}e_\beta = -\frac{3}{2}e_\alpha + \frac{\sqrt{3}}{2}e_\beta \end{aligned}\right\} \qquad (2c)$$

Line-to-Line Fault (Phases b and c)

Conditions at the fault are:

$$i_b = -i_c;\ i_a = 0;\ e_b = e_c$$

From (3b)

$$i_\alpha = i_0 = 0;\ e_\beta = 0$$

For a system symmetrical before the fault, the zero-sequence network is not involved. The β-network is shorted at the point of fault. The α-network is unaffected when $x_d'' = x_q''$, but when $x_d'' \neq x_q''$ voltages are generated in the machines which affect e_α. (see appendix B). At the fault,

$$\left.\begin{aligned} e_a &= e_\alpha \\ e_b &= e_c = -\frac{1}{2}e_\alpha \end{aligned}\right\} \qquad (3c)$$

Double Line-to-Ground Fault (Phases b and c)

Conditions at the fault are:

$$i_a = 0;\ e_b = e_c = 0$$

From (3b)

$$e_\beta = 0;\ e_\alpha = 2e_0;\ i_\alpha = -i_0$$

It follows that

$$2e_0 = -2Z_0(p)i_0 = 2Z_0(p)i_\alpha = e_\alpha \qquad (4c)$$

The equivalent circuit to replace the fault in the α-network is therefore $2Z_0(p)$. The β-network is shorted at the point of fault. When $x_d'' = x_q''$, there is no mutual coupling between the α- and β-networks, but when $x_d'' \neq x_q''$, voltages are generated in the machines which affect e_α and e_0. (See appendix B.)

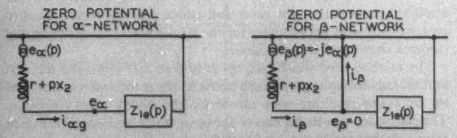


Figure 19. Equivalent circuit for line-to-line fault for use in determining harmonic currents and voltages

At the fault,

$$\left.\begin{aligned} e_a &= e_\alpha + e_0 = 3e_0 = \frac{3}{2}\, e_\alpha \\ e_b &= e_c = 0 \end{aligned}\right\} \qquad (5c)$$

In figures 18, 19, 20 are shown the equivalent circuits for line-to-ground, line-to-line, and double line-to-ground faults at the terminals of a synchronous generator with series impedance connected to any symmetrical external system in which the positive- and negative-sequence impedances are equal. $Z_{1e}(p)$ and $Z_{0e}(p)$ are the operational expressions for the positive- and zero-sequence impedances

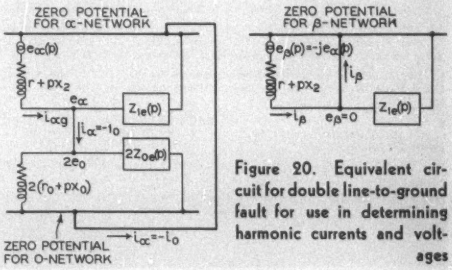


Figure 20. Equivalent circuit for double line-to-ground fault for use in determining harmonic currents and voltages

of the external system. $r_0 + px_0$ is the zero-sequence impedance of the generator. The positive- and negative-sequence impedances of the generator to currents of frequencies other than fundamental is approximately $r + px_2$ except for very high frequencies. This is also the α and β impedances to them.

Except for voltages of fundamental frequency which are determined by the method of symmetrical components, the equivalent circuits of figures 18, 19, 20 can be used to determine all other components of current and voltage. The principal natural-frequency terms are calculated by the application of a voltage at the point of fault equal and opposite to the initial steady-state voltage. The point of application of voltages generated when $x_d'' \neq x_q''$ is taken in the machine.

Resonance to Harmonics

Harmonic voltages are generated in machines in which $x_d'' \neq x_q''$. The external impedance which will cause resonance for various types of faults can be determined from the equivalent circuits as follows:

From equation 2c and figure 18, resonance for a line-to-ground fault can occur either in the unfaulted β-circuit or in the α-circuit. For resonance to the nth harmonic in the β-circuit there is the equation:

nx_2 = negative reactance component of $Z_{1e}(p)$

For resonance in the α-circuit,

nx_2 = negative reactance component of $\frac{r_0 + px_0}{2}$, $\frac{Z_{0e}(p)}{2}$, and $Z_{1e}(p)$ in parallel.

It is thus possible to have resonance to one harmonic in the α-circuit and to another in the β-circuit.

For the line-to-line and the double line-to-ground faults resonance can only occur in the α-circuit. For the line-to-line fault it will occur when

nx_2 = negative reactance component of $Z_{1e}(p)$

For the double line-to-ground fault when

nx_2 = negative reactance component of $2(r_0 + px_0)$, $2Z_{0e}(p)$, and $Z_{1e}(p)$ in parallel.

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Discussion

D. E. Brainard (General Electric Company, Schenectady, N. Y.): The authors have pointed out that they controlled the point on the voltage wave at which the short circuits were applied. By choosing the point of maximum linkages they obtained the maximum possible overvoltage. When the usual random shots must be accepted, it is necessary to estimate the maximum overvoltage for a given machine by observing the point on the cycle at which each value of overvoltage occurs.

This procedure was applied in the case of a 26-pole, 1,250-kva 600-volt generator having a copper amortisseur winding without connected end rings. With the machine operating at 0.33, 0.66, and 1.0 per unit voltage, single phase, line-to-line, sudden short circuits were applied. The values of the ratio of the maximum voltage obtained on the open phase to the voltage before the short are plotted in figure 1. These voltages were measured by an oscillograph both from open line to neutral and from open line to shorted lines. The angle was determined from the oscillogram of the voltage between the two terminals which were shorted.

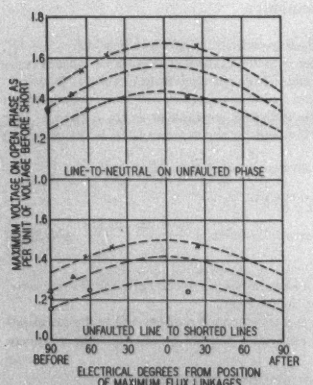


Figure 1. Open-phase voltages following single-phase line-to-line short circuits (as a function of linkages in shorted phase when shorted)

Tests on 26-pole 1,250-kva 600-volt machine having copper amortisseur winding without connected end rings

$x_q''/x_d'' = 1.33$ by static test at 1.0 per unit current

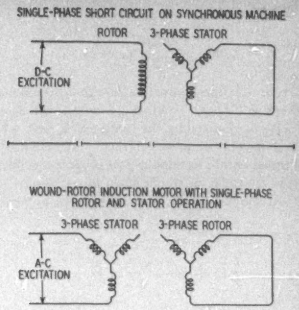
Per unit voltage before short as follows:

$x = 0.33$ $\Delta = 0.66$ $0 = 1.00$

A curve drawn through the test points gives a maximum ratio for the line-to-neutral case of 1.68 for the short from 0.33 voltage. The short-circuit current for this case is of the order of rated current for which condition static tests show a ratio of $x_q''/x_d'' = 1.33$. The formula given in the paper gives a maximum voltage ratio of 1.66 with which the test is in substantial agreement. It is to be noted, however, that the line-to-line-voltage ratio reaches a maximum of only 1.5 for the same conditions.

J. H. Fortenbach (nonmember; General Electric Company, Schenectady, N. Y.): The problem of single-phase short circuit on a synchronous machine is analogous to the problem of a wound-rotor induction motor when operating with single-phase excitation on the stator and with only one phase short-circuited on the rotor. The chief differences are that the induction motor is a round-rotor machine and the excitation is alternating current rather than direct current. Figure 2 illustrates the analogy.

Figure 2



We have known for many years that operation of a wound-rotor induction motor in such a manner produced abnormal voltages across the open phases. From the various tests which were made in the past, it was found that under these conditions the voltage across the open phase of either the rotor or stator might be in the order of ten times normal.

The most recent tests which we made on a three-phase wound-rotor induction motor with single-phase rotor and stator were taken in 1931. These were made on an 8-pole 15-horsepower 900-rpm 220-volt three-phase 60-cycle motor. The motor, at first unexcited, was driven and held at a constant speed. Single-phase normal voltage was then suddenly applied across two stator lines. The oscillogram (figure 3) shows a typical result for the case when the machine was driven at 900 rpm.

By assuming that the mutual inductance between a stator and a rotor phase is proportional to the cosine of their relative angular displacement and that the rotor and stator resistances are equal to zero, we were able to calculate (for the steady state) the voltages and currents shown by the oscillogram.

The method used was to set up in operational form, the self and mutual induced voltages in each phase of the rotor and stator. The six equations resulting were solved for the steady state condition. The calculated results for one of the open stator and one of the open rotor voltages are shown by figure 4.

The circled points are the tested values taken from the oscillogram.

Figure 3

A—Open-stator voltage; one centimeter = 328 volts

B—Open-stator voltage; one centimeter = 518 volts

C—Rotor current; one centimeter = 115 amperes

D—Applied stator voltage; one centimeter = 622 volts

E—Open-rotor voltage; one centimeter = 516 volts

F—Open-rotor voltage; one centimeter = 258 volts

E. M. Hunter (General Electric Company, Schenectady, N. Y.): This study of overvoltages caused by unbalanced short circuits described by the authors is illuminating when viewed in the light of operating experiences reported on ungrounded-neutral systems. The disturbances resulting from overvoltages during ground faults on ungrounded neutral systems have been described frequently in the technical press. They have been attributed to "arcing grounds." Numerous attempts have been made to reproduce "arcing grounds" during staged tests with little success, which has led to the suspicion that the overvoltages that have occurred should be explained in some other way.

The authors' figure 17 shows the areas in which overvoltages may occur. A study of this figure indicates that the chances of obtaining the overvoltages described are greater on the ungrounded-neutral system. It would appear that at least some of the overvoltages previously attributed to "arcing grounds" have actually resulted from the phenomena described in this paper.

The authors have suggested that to reduce the overvoltages, the generators be equipped with amortisseur windings. The ground

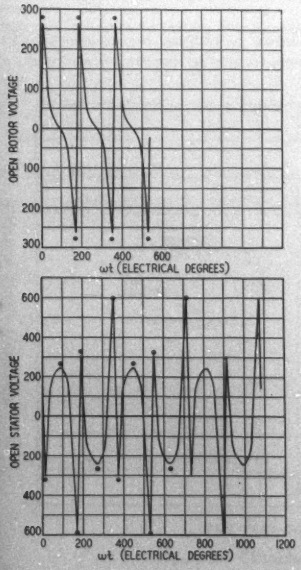


Figure 4

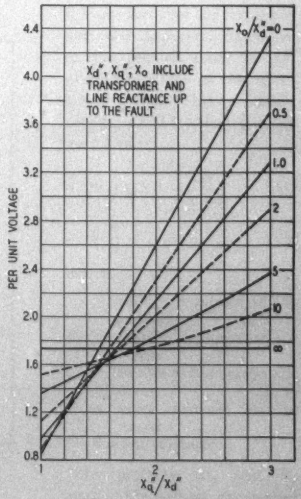


Figure 5. Line-to-ground fault—maximum voltage of the unfaulted phases in per unit of crest voltage before the fault. Constant rotor flux linkages—resistance and capacitance neglected—maximum flux linkages

fault neutralizer (Petersen coil) is also effective in reducing them. On a system with a neutralizer the zero-sequence impedance is infinite. Accordingly, during line-to-ground faults, there is no flow of positive or negative fault current. When the neutralizers are located on the system, there is little negative-sequence current flowing to produce the excitation necessary for the overvoltages. Referring again to the authors' figure 17, curves *F*, *G*, *H*, and *I* represent the areas where resonance occurs and overvoltages may be serious for single and double line-to-ground faults on ungrounded neutral systems. These areas are eliminated with ground-fault neutralizers on the system.

Edith Clarke, C. N. Weygandt and **C. Concordia:** Mr. Brainard's tests illustrate the effect of closing angle and show that in order to obtain consistent results, control of this angle is essential. He also finds that the ratio of line-to-line voltage after the fault to that before the fault is smaller than the corresponding line-to-neutral voltage ratio. In the paper it is shown that theoretically the relation is: (line-to-line voltage ratio) = 0.866 (line-to-neutral voltage ratio).

The results presented by Mr. Fortenbach are particularly interesting since they show such an excellent theoretical check of the observed steady-state voltage wave and since they demonstrate the essential similarity of synchronous and induction machines as far as these overvoltages are concerned.

As brought out in the paper, a line-to-line fault was studied in detail because it may result in the highest voltages and because it is the type most affected by changes in x_q''/x_d''. To show the effect of x_q''/x_d'' on voltages arising from line-to-ground faults without capacitance, figure 5 of this closure has been included. The curves of figure 5 show that for small x_q''/x_d'' the overvoltage at the fault increases with increasing x_0, while for large x_q''/x_d'' the situation is reversed and the overvoltage decreases with increasing x_0. It has been pointed out by Mr. Hunter that the effect of a ground fault neutralizer is to make $x_0 = \infty$, so that voltages at the fault would then be practically limited to the value shown in the figure for $x_0 = \infty$.

For the case studied, the open phase voltages are given by:

$$e_b = -\frac{3}{2}e_\alpha + \frac{\sqrt{3}}{2}[e_\beta + \cos(\theta - \alpha)]$$

$$e_c = -\frac{3}{2}e_\alpha - \frac{\sqrt{3}}{2}[e_\beta + \cos(\theta - \alpha)]$$

where

$$e_\alpha = -x_0\frac{[x_0 + 2x + 2y\cos 2\theta]\sin\theta - 4y\sin 2\theta(\cos\theta - \cos\theta_0)}{[x_0 + 2x + 2y\cos 2\theta]^2}$$

$$e_\beta = 2y \times \frac{(x_0+2x+2y\cos 2\theta)\sin\theta\sin 2\theta - [4y + 2(x_0+2x)\cos 2\theta](\cos\theta - \cos\theta_0)}{[x_0 + 2x + 2y\cos 2\theta]^2}$$

Resonant Nonlinear Control Circuits

By WILLIAM T. THOMSON
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Synopsis: The resonant type of nonlinear circuit containing a resistance, a condenser, and a saturable-core reactor is finding a number of applications in the various engineering fields,[1] and an analytical treatment has here been developed to add to the understanding of the behavior of such circuits. Certain features of the superposition of a d-c magnetizing force on the reactor are discussed. A method of increasing the sensitivity of this d-c controlled circuit, with a mathematical analysis for the criteria of stability and amplification is given. Finally, a specific application of the circuits discussed to a sensitive and stable power controlling device is described.

THE GENERAL characteristics of the resonant nonlinear circuit have been known for some time.[2] However, in order to determine specifically the behavior of such circuits, an analytical treatment is necessary. With such an analysis it is possible to calculate the critical resistance, the critical voltage and the critical current, and a better understanding of such circuits is gained.

The Series Circuit

For the general characteristics of the nonlinear circuit, the reader is referred to the paper on nonlinear circuits by C. G. Suits.[3] For orientation purposes, however, some of the properties of the series nonlinear circuit will be briefly reviewed. Figure 1 illustrates the typical volt-ampere relation of such circuits. The observations to be noted here are:

1. Upon reaching a certain critical voltage, the current takes an abrupt rise.
2. The steepness of this rise in the critical region is some function of the resistance.
3. If this resistance is reduced to a value less than the critical resistance, the circuit becomes unstable in the critical region and displays a hysteresis effect. In this unstable region, the slope dE/dI of the curve becomes negative. See figure 4.
4. The magnitude of the current jump is some function of the condenser size.

The peculiar volt-ampere relation found in such circuits is due to the joint action of saturation of the iron and the partial resonance of the circuit. Figure 2 is an oscillogram illustrating the cumulative action of the current jump in the unstable region.

With these points in mind, the problem will be treated analytically. Referring to the unstable curve of figure 1, there exist two points on the curve where $dE/dI = 0$. Since with a critical resistance in the circuit these two points merge into one, the value of the critical resistance can be obtained by equating the two expressions for the current when $dE/dI = 0$.

Unfortunately very little is known of the nonlinear differential equation encountered for such circuits, and therefore one must resort to the use of an equivalent sine wave and treat the problem vectorially. With such a method, it is obvious that the reactance and the apparent resistance of the reactor must be expressed in terms of the effective current. This is readily accomplished by the following vector relation:

$$X_L = \frac{1}{I}\sqrt{E_L^2 - \left(\frac{W}{I}\right)^2} \qquad (1)$$

$$R_L = \frac{W}{I^2} \qquad (2)$$

where

X_L = effective reactance of the reactor
R_L = apparent resistance of the reactor
E_L = effective voltage across the reactor
W = watts consumed by the reactor
I = effective current

In plotting X_L and R_L against the current, the curves

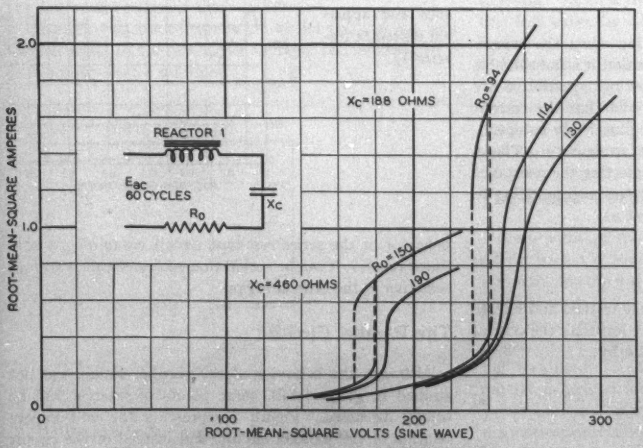

Figure 1. Characteristics of the series circuit

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1. For all numbered references, see list at end of paper.

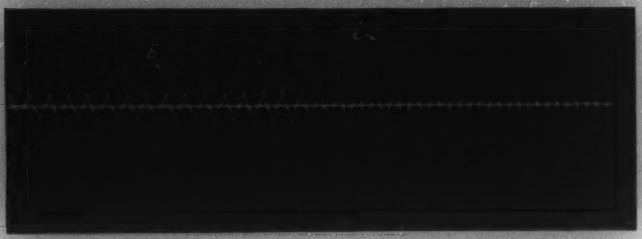


Figure 2. Current jump at critical voltage

appear as in figure 3. Since the critical condition always occurs on the negative-slope portion of the reactance curve, it is only necessary to fit an equation over this region. The equation best fitting these curves is a rectangular hyperbola with displaced axis, and R_L and X_L can be expressed as follows:

$$R_L = \frac{A}{\alpha + I} + K_1 \qquad (3)$$

$$X_L = \frac{B}{\beta + I} + K_2 \qquad (4)$$

where A, α, B, β, K_1 and K_2 are constants of the reactor. The constants are calculated by taking three points covering the desired interval of the curve.

Using these expressions in the voltage equation;

$$E = I\sqrt{R^2 + X^2} \qquad (5)$$

where

$R = R_0 + R_L$, the sum of the series and the apparent resistance of the reactor

$X = X_L - X_c$, the difference in the reactive impedances,

equation 5 can be differentiated with respect to the current and set equal to zero.

$$R\left(R + I\frac{dR_L}{dI}\right) + X\left(X + I\frac{dX_L}{dI}\right) = 0 \qquad (6)$$

The difficulty with this last equation when the expressions for X_L and R_L are substituted is that it is not solvable mathematically. However, by plotting equation 6 for various values of resistance it is found that the current for the maximum negative dE/dI is practically independent of the resistance. This is shown in figure 4. Therefore by differentiating equation 6 neglecting the resistance term and setting it to zero, the current corresponding to the critical stable voltage is expressible as:

$$I_m = -2\beta + \sqrt{\beta^2 + \frac{3\beta B}{(X_c - K_2)}} \qquad (7)$$

Also, the current corresponding to the critical and release voltages for the case with a resistance less than the critical value can be expressed approximately by;

$$I_1 = -\beta + \sqrt{\frac{\beta B}{X_c - K_2 - R_0}} \qquad (8)$$

$$I_2 = -\beta + \frac{B}{X_c - K_2 + 2R_0} \qquad (9)$$

and the critical resistance found from equating the two equations above is;

$$R_0 = -\frac{B}{8\beta} - \frac{1}{2}(X_c - K_2) + \sqrt{\left(\frac{B}{8\beta}\right)^2 + \frac{3B}{8\beta}(X_c - K_2)} \qquad (10)$$

The critical stable voltage with a critical resistance in the circuit is then found by substituting R_0 and I_m in equation 5.

The equations derived in this analysis are found to be in very good agreement with the experimental values, the test being performed with four different reactors and various sizes of condensers. The tabulation of results with a comparison with the experimental values for one of the reactors is given in table I.

It is evident from these equations that the current jump increases as X_c decreases, as observed in figure 1, and when the value of the capacitance is equal to the constant K_2 of the reactor, the current rises to a very large value. Also, for this condition, the critical resistance will be equal to zero. For any resistance less than the critical value, the same analysis can be made, in which case the values of I_1 and I_2 must be used in calculating the critical and the release voltages. In summarizing the behavior of the series resonant circuit containing a nonlinear reactor, it can be stated that such a circuit is voltage sensitive in the critical region.

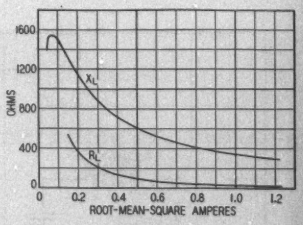


Figure 3. Reactance and apparent resistance (reactor 1)

The Parallel Circuit

Although the behavior of the parallel circuit was not studied in great detail, some points of interest will be briefly discussed. Figure 5 represents the volt-ampere relation of the parallel circuit, and instead of the circuit being voltage sensitive it is known to be current sensitive.

Table I (Reactor 1)

Calculated Values				Experimental Values	
X_c	R_0	I_m	E	R_0	E
26	0				
43	18	2.48	322	30	323
93	55	1.13	282	60	284
188	113	0.653	245	114	248
272	151	0.490	218	145	224
355	178	0.395	200	170	205
460	206	0.305	188	190	186

As in the series circuit, the critical region characterized by the negative slope is some function of the resistance.

One thing of interest here is that the critical voltage and current for the reactor branch of the parallel circuit are essentially the same as those for the series circuit. Starting from the expression,

$$\frac{dI}{dE} = \frac{dI}{dI_L} \cdot \frac{dI_L}{dE} \tag{11}$$

the critical condition is found when $dI/dI_L = 0$, since dI_L/dE cannot become zero for any region. Neglecting the resistance,

$$I = -I_L \left\{ \frac{X_L - X_c}{X_c} \right\} \tag{12}$$

and when

$$\frac{dI}{dI_L} = 0$$

$$I_L \frac{dX_L}{dI_L} + X_L - X_c = 0 \tag{13}$$

When the expression for X_L is substituted into equation 13, the resulting equation becomes;

$$I_L = -\beta + \sqrt{\frac{\beta B}{X_c - K_2}} \tag{14}$$

and it is seen that this is essentially the same equation as that of the series circuit.

Since the reactor voltage is known for this current, and is also equal to the condenser voltage, the line current I is found by vector addition.

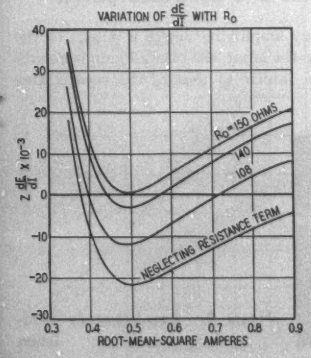
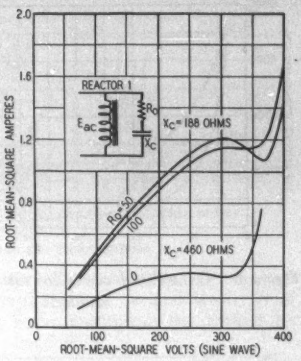


Figure 4

Figure 5. Characteristics of the parallel circuit



The Generalized Form of Reactance and Apparent Resistance

From the foregoing it is evident that in order to predict the behavior of the circuits discussed, the reactance and the apparent resistance of the reactor are necessary. The two quantities can be predicted approximately for any reactor provided certain experimental data for the iron are at hand.

The first of these is the effective permeability curve shown in figure 6. Since the reactance is

$$\frac{0.4\pi N^2 A}{l} \mu \times 10^{-8}$$

from this permeability curve, it is possible to determine the reactance of any reactor using the same iron.

In the same manner, the apparent resistance of any reactor can be obtained from the second curve of figure 6. This curve was calculated from the density-core-loss data and the a-c magnetization curve. The apparent resistance curve is obtained by multiplying the values of this last curve by $(N/l)^2$ and the number of pounds of iron used.

Although, in the method described above, the effect of the leakage flux and the air gap are assumed to be the same as that of the test reactor from which the data is obtained, the results obtained by this method agree very well with the actual curves.

The Series Circuit With D-C Saturation

Some points of interest in regards to the series resonant circuit with a d-c magnetizing force superimposed on the iron-core reactor was investigated mainly from the utility point of view.

To superimpose the d-c flux, the well-known three-legged reactor commonly used in controlling theater lighting was used. If the volt-ampere relation for such a reactor is plotted for various values of d-c saturation, it would be found that the effect of the d-c is to shift the magnetization curve to the right.[4] Also, the d-c saturation decreases the maximum of the reactance curve and

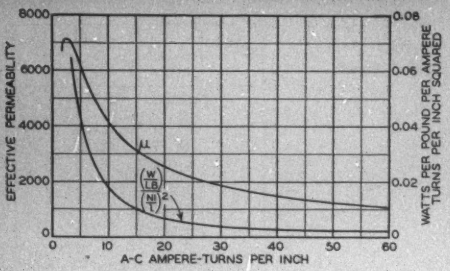


Figure 6. Generalized curves for reactance and apparent resistance

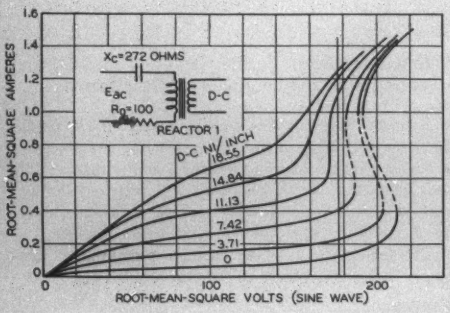


Figure 7. Series circuit with direct current superimposed

shifts it in the same direction. It will be found here that for a large value of a-c ampere-turns per inch, the reactance curves all come together and, therefore, in this region, the d-c controllability is greatly decreased. This will then determine for the d-c controlled circuit, the upper limit of the a-c ampere-turns per inch. The lower limit will obviously correspond to the peak of the reactance curve with zero d-c saturation. For the iron used in this investigation (Allegheny dynamo grade) the useful range of the a-c ampere-turns per inch is roughly between four and 30.

When the three-legged reactor is used in series with a condenser and a resistance, the volt-ampere relation will appear as in figure 7. Here it is noted that the effect of increasing the d-c saturation is to shift the curve upward and the critical voltage to the left.

When this circuit is operated with a constant voltage and the circuit controlled by the d-c coil, the locus of the a-c current will be along a vertical line such as that shown in the diagram, and it is seen that the change in the a-c current is greatest between certain values of d-c saturation as shown by curves 2 and 3. Therefore, if a very sensitive control is desired, it is possible to bring the circuit up to this sensitive level by means of another coil and operate the circuit about this region. By connecting two such circuits biased to this sensitive level in a bridge form, the initial output can be made equal to zero and the disturbing effect of the line-voltage fluctuation greatly eliminated.

When operating with a d-c bias, some difficulty is encountered when the controlling power is very small. This is due to the fact that with a d-c level of magnetization, there is a voltage induced in the control coil which may render the circuit unstable. With a d-c level of saturation, the flux variation in the two a-c legs of the reactor becomes unequal. The difference in these two fluxes must then flow through the center leg of the reactor, thereby inducing a voltage in the control coil. An analysis from the magnetization curve indicates that this unbalance of flux is mainly in the opposite direction to that of the control coil, and therefore is demagnetizing. For these reasons, it is advantageous to prevent this unbalance of flux from flowing in the center leg. This is accomplished by placing a short-circuited coil around the d-c leg.

With this short-circuited coil, an interesting difficulty was encountered. If the resistance R_0 in the circuit is reduced to a value less than the critical resistance, the circuit goes into a low-frequency oscillation. The oscillogram of figure 8 illustrates this phenomenon. It is found that the frequency of this oscillation is mainly a function of the d-c magnetizing force. This low-frequency oscillation, however, was checked by increasing the resistance to a value greater than the critical resistance of the circuit.

A Regenerative Method of Increasing the Sensitivity of the D-C Controlled Circuit

Noting that in any amplifying device if a part of the output is fed back to the input, the over-all gain is greatly increased, a scheme similar to that of the regenerative

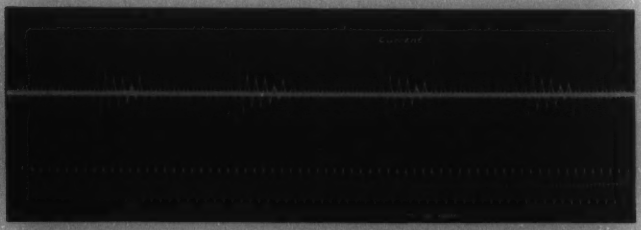


Figure 8. Low-frequency oscillation

radio circuit can be used to increase the sensitivity of the d-c controlled circuit.

Figure 9 indicates the circuit diagram of the regenerative amplifier. The a-c output obtained across the condenser is rectified by means of the copper-oxide rectifier to supply the d-c load, the circuit being controlled by the d-c saturation. The amplification is obtained by feeding the output current through a regeneration coil wound on the same leg as the d-c control coil, the effect being to increase the total control of the circuit. With such a scheme, if the number of turns on the regeneration coil is too large, the circuit becomes unstable and therefore some criteria for the stability as well as the amplification must be developed. This is done by first assuming a straight-line relation between the input and the output current and developing the mathematics by a step-by-step process.

Starting with an input of i_0, the initial output current will be hi_0, where h is the slope of the output current for zero regeneration. This output flowing through the regeneration coil produces an additional control of $(nh/N)i_0$, which must be added to the initial control to give the effective control. Continuing with this process, the resulting equation is a geometric series,

$$I_{output} = hi_0 \left\{ 1 + \left(\frac{nh}{N}\right) + \left(\frac{nh}{N}\right)^2 + \left(\frac{nh}{N}\right)^3 + \cdots \right\} \qquad (15)$$

the sum of which is given by the following equation:

$$I_{output} = hi_0 \left\{ \frac{1}{1 - \left(\frac{nh}{N}\right)} \right\} \qquad (16)$$

where

n = number of turns on the regeneration coil
N = number of turns on the control coil
h = slope of the initial curve with no regeneration
i_0 = control current
I_{output} = output current with regeneration

From this equation it is evident that the circuit is stable as long as (nh/N) remains less than one, and therefore this becomes the criterion for stability. The amplification factor is given by the bracketed term. For the case where the initial response curve deviates greatly from the linear relation, better results can be obtained by using the following equation,

$$I_{output} = I' \left\{ \frac{1}{1 - \left(\frac{nh'}{N}\right)} \right\} \qquad (17)$$

where

I' = actual current for no regeneration, at the point in consideration
h' = actual slope of the curve corresponding to the point in question

To verify this equation, several predeterminations were made, one of which is shown in figure 9. In this diagram, the lower curve is the output plotted in terms of the input for no regeneration, while the upper solid curve represents the output of the same circuit with regeneration. The dotted curve is the predetermined output calculated from equation 17, and it is seen that the agreement between the theoretical and the experimental curves is very close.

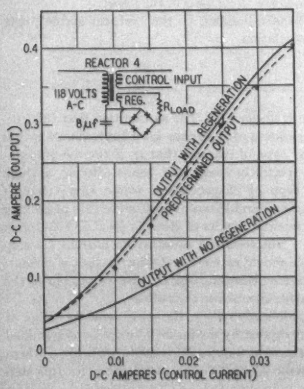


Figure 9. Regenerative amplifier

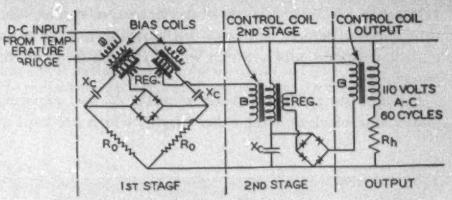


Figure 10. Control circuit of radiation meter

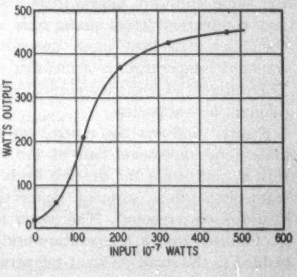


Figure 11. Output curve of the radiation meter

A Specific Application to the Radiation-Meter Control Circuit

The circuits discussed in this paper have been successfully applied to a specific engineering problem in connection with the radiation meter. The function of this meter is to measure the net radiation taking place at the earth's surface, such data having important applications in the study of plants.

These measurements must be taken continuously for a long period extending into years. It is necessary to main-

tain control without the use of contactors, relays, or other intermittent devices and also without the use of units, such as vacuum tubes, which would require frequent replacements.

Briefly, the radiation meter consists of two exposure plates, one black and the other bright, which are kept at

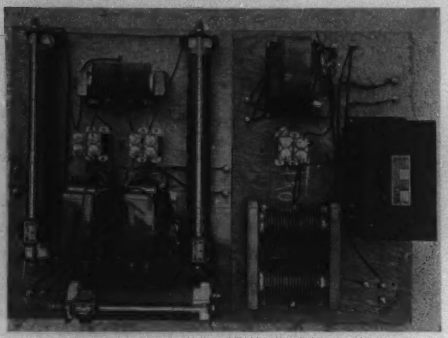


Figure 12

the same constant temperature. Since the convection and conduction losses under this condition are equal, the differential heat input necessary to maintain this constant temperature is a measure of the net radiation. This differential power is recorded continuously by a graphic differential wattmeter.

Figure 10 shows the control for one of the exposure plates and represents half of the radiation meter. In this R_h represents the heating loads for one of the constant-temperature surfaces, connected in series with a saturable-core reactor. The power for the control input is obtained from a temperature-bridge thermometer imbedded in the same constant-temperature surface. For a two-degree deviation from the set temperature, the temperature bridge sends a signal into the control circuit sufficient to produce maximum heating at the heater coil.

The first stage of this control circuit is connected in a bridge to overcome any effect of line voltage fluctuation, and each arm of the bridge is biased to the most sensitive level by means of the bias coils. The output of this bridge is then rectified by means of the copper-oxide rectifier and fed through the regeneration coils and the control coil of the second stage. The connection of the regeneration coils in the bridge is such that it aids the bias and the control signal in the first leg and opposes the bias in the second leg, thereby producing a maximum of unbalance. In the same manner, the output of the second stage is rectified and fed through the regeneration coil and the control coil of the final stage. Here the bridge circuit is not necessary since the control signal is sufficiently large and the effect of the line voltage fluctuation relatively small.

The amplification obtainable from such a circuit is quite striking as shown by the curve giving the over-all characteristics of the control circuit. (See figure 11.) It is seen here that an input of 450×10^{-7} watts is sufficient to control an output of approximately 450 watts, thereby resulting in a power amplification of approximately 10,000,000. Such a circuit is quite inexpensive to build, and once the control is adjusted, the circuit will require practically no replacement of parts or upkeep for service. The simplicity of this control circuit is shown by the photograph of figure 12.

In conclusion it may be stated that the greatest utility of such circuits will undoubtedly be in control circuits where large amounts of power must be continuously controlled by means of a relatively small input. As more and more becomes known of such circuits, the resonant type of nonlinear circuit will find a definite place in the various engineering fields.

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3. Studies in Nonlinear Circuits, C. G. Suits. AIEE Transactions, June 1931, pages 724–36.

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Discussion

P. H. Odessey (Heyer Products Company, Belleville, N. J.): In Mr. Thomson's paper, the derivation of critical quantities associated with ferroresonance embodies a number of concepts that are not quite clear. In particular, the following points are noted with respect to approximations and assumptions made in deriving the expressions for current and critical resistance as defined in this paper; the numbers of equations are those used in the paper.

1. The current (7) corresponding to the "critical stable" voltage is derived from the relation

$$\frac{d^2E}{dI^2} = 0$$

whereby the resistance is neglected. The assumption that this current is practically independent of resistance is an approximation that is valid for a particular type of reactor, that is, if the a-c volt-ampere characteristic is relatively steep and bends sharply at high saturation. For the type of characteristic whose slope changes slowly with saturation considerable error is introduced by neglecting resistance. The experimental results of Rouelle (*R.G.E.* 1934) give evidence of this effect. The resulting equation for current (7) contains a radical and hence should reveal two distinct values of current. No explanation is given for discarding one of these values nor of the significance of the negative sign before the radical.

2. When current is defined by (7), the corresponding value of critical stable voltage evaluated by means of (5) must be determined by using the value of critical resistance R_s defined by (10). As there is no interrelation between I_m and R_s the justification for this step

is not quite clear. Thus, employing the criteria of stability,

$$\frac{dE}{dI} = 0$$

two "approximate" equations are given for the currents corresponding to the release voltages and contain a resistance term R_0. Since equation (6) was stated to be mathematically unsolvable when resistance was included, it is not quite clear how (8) and (9) were derived. As the forms of these equations indicate, their derivation does not follow as an approximation made after solving (6) by neglecting resistance.

3. Since these two equations are identical for the condition of critical stable voltage, the analytic expression for critical resistance (10) is obtained by equating (8) and (9). But since (7) already expresses the value of current corresponding to the critical stable voltage, then (8) and (9) could each be made identical with (7) and two other equations for critical resistance could be obtained. This discrepancy is not explained.

4. If, as in the presentation, the critical resistance is properly expressed, then by substituting this value (10) in the current equations (8) or (9) we should obtain equivalence with I_m defined by (7). There is, however, no assurance that this may be attained even approximately. It appears, therefore, that the critical resistance and I_m are entirely unrelated, yet must be employed together in the evaluation of critical stable voltage by means of (5).

5. In view of the assumptions and approximations, the results indicate an unusually high degree of accuracy although not consistent. For example, corresponding to a 40 per cent error in R_0 ($X_c = 43$, table I) the error in critical stable voltage is 0.3 per cent whereas for a 0.88 per cent error in R_0, the error in voltage is 1.21 per cent ($X_c = 188$). Thus, it appears that any error in R_0 does not materially affect the value of voltage. Although not given, it would have been interesting to observe the check on I_m, I_1 and I_3, and so justify some of the approximations.

W. T. Thomson: In reply to Mr. Odessey's discussion, I will endeavor to justify the assumptions made and indicate why it is possible to arrive at accurate results for the critical voltage using the more inaccurate values of critical current and resistance. Dimensions of one of the reactors for which the results were published are given together with the sample calculations (see figure 2).

Although my investigation was limited to a certain type of reactor (three-legged reactor) using a certain grade of iron, this type

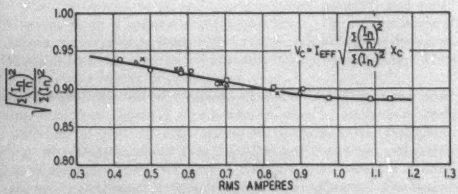


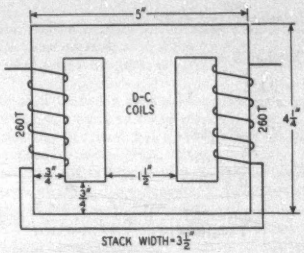
Figure 1. Reduction in voltage across condenser due to harmonics

$$V_c = I_{eff}\sqrt{\frac{\Sigma\left(\frac{I_n}{n}\right)^2}{\Sigma\,(I_n)^2}}\,X_c$$

of reactor is extensively used for various control purposes and quite frequently with iron of similar characteristics. It seems therefore that Mr. Odessey's criticism that the method is applicable only to a very special and limited condition is not justifiable.

The apparent resistance of the reactor defined by the expression $R_L = W/I^2$ is of course an approximation for circuits containing iron. It is agreed that for small values of current this error is not great. Let us investigate then the discrepancy for a large value of current. Assume in figure 3 that $I_1 = 0.8I$ when $I = 1.2$ amperes. R_L from the curve is 15 ohms and its value based on I_1 is $15/0.8^2 = 23.5$ ohms. The per cent error is therefore considerable but the difference in ohms is only 8.5. In the calculation of the voltage this small error in a

Figure 2. Dimensions of reactor 1



term which is small compared to the reactive term produces practically no error when combined at right angles.

It may be stated that in order to obtain values for the more correct definition based on the fundamental current I_1, special equipment such as the harmonic analyzer is necessary, and for the average person to whom such equipment is not available, an approximation of this type is not out of order as long as it produces negligible errors in the final results. The writer would like to point out that Mr. Odessey in his paper ("Critical Conditions in Ferroresonance") makes an approximation which is far more serious in assuming the first term of equation 4 to be an ellipse. This term of the equation is an ellipse only when the total resistance is constant. The apparent resistance which must be considered as part of the total resistance varies greatly with the current as shown in figure 3.

Equations 8 and 9 are empirical. When $R_0 = 0$, they are the roots of equation 6 with the resistance omitted. The expression for R_0 given by equation 10 is therefore empirical and is unrelated to I_m as stated in the paper. To show that equation 10 is not a special equation limited only to a certain reactor, the following results obtained for three other three-legged reactors made with the same iron are given.

Reactor 3			Reactor 2			Reactor 4		
X_c	R_0 (Calc.)	R_0 (Exp.)	X_c	R_0 (Calc.)	R_0 (Exp.)	X_c	R_0 (Calc.)	R_0 (Exp.)
93	57	63	25	8	10	93	47	56
187	120	120	43	24	26	187	108	107
272	162	164	93	49	50	272	146	139
355	194	182	187	75	68	339	172	158
			272	87	75			

As stated before, a few ohms error one way or another when combined at quadrature with a much larger reactive term produces negligible error in the calculation of the voltage.

Equation 7 will always give a value of current in the unstable region. It is apparent from figure 1 that with a critical stable condition the current may have a wide range of values and still give the same critical voltage. Therefore even if this current varied with resistance for other types of iron, very little error would be produced in the critical voltage provided the current obtained is within the unstable region.

I fail to see any physical significance of the negative sign in front of the radical in equation 7. The equations as given in my paper apply only in as far as they fit the experimental curves for X_L

and for this case the negative value of the effective current seems meaningless.

Appendix

I. Sample Calculation

For Reactor 1:

$$X_L = \frac{360}{0.115 + I} + 26$$

Therefore $B = 360$

$\beta = 0.115$
$K_3 = 26$

For $X_c = 272$ ohms:

$$R_0 = -\frac{360}{8 \times 0.115} - \frac{1}{2}(272 - 26) + \sqrt{\left(\frac{360}{8 \times 0.115}\right)^2 + \left(\frac{3 \times 360}{8 \times 0.115}\right)}(272 - 26) = 151 \text{ ohms}$$

$$I_m = -2 \times 0.115 + \sqrt{(0.115)^2 + \frac{3 \times 0.115 \times 360}{272 - 26}} = 0.49 \text{ ampere}$$

therefore

$X_L = 620$
$R_L = 100$

From figure 1

$$\sqrt{\frac{\Sigma\left(\frac{I_n}{n}\right)^2}{\Sigma I_n^2}} = 0.93$$

$$E = 0.49\sqrt{(100 + 151)^2 + (620 - 0.93 \times 272)^2} = 218 \text{ volts}$$

II. Data for Regeneration Curve, Figure 9

Reactor 4:

Control and regeneration coils on center leg

$n = 200$
$N = 2{,}000$

therefore

$$I_{dc} = I' \left\{\frac{1}{1 - 0.1K}\right.$$

Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 15 pages appear discussions submitted for publication, and approved by the technical committees, on previously published papers presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Matrices in Engineering

Discussion and author's closure of a paper by Louis A. Pipes published on pages 1177–90 of volume 56, 1937, AIEE TRANSACTIONS (September 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the basic sciences session of the winter convention, New York, N. Y., January 26, 1938.

Joseph Slepian (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Linear systems of equations such as are continually met in practical engineering problems, present their primary data to us in the form of a rectangular array of numbers, the coefficients of the various terms in the set of equations. All the information which it is possible to obtain mathematically about the physical system represented by the equations is buried or latent in this array of numbers. Whatever new information we succeed in arriving at about the system by purely mathematical means will be reached ultimately only by successions of arithmetical operations upon the numbers of the array. Hence, we may say that this rectangular array of numbers is the appropriate manner of mathematical description or representation of the physical system for which the linear system of equations was set down. Given the sufficient description of the kind of equations for which the numbers serve as coefficients, the array gives all the information about the system with no irrelevancy. Both the position in the array of a number and its magnitude are significant in determining the result of any actual calculation.

Thus the matrix as an entity presents itself naturally and easily from the study of systems of linear equations. The various manipulations we make upon linear equations amount always to the calculation of new (usually simpler) matrices from given matrices. Thus the idea of a matrix calculus arises.

Two particular ways of calculating a new matrix from two other matrices keep recurring in practical problems. Because of their similarity to the arithmetic operations of addition and multiplication of ordinary numbers, they are called matrix addition and matrix multiplication. Thus we have a matrix algebra which is similar, except for one important property, to ordinary algebra. The beauty and utility of this matrix algebra applied to important every day problems in electrical engineering are well brought out in the very excellent paper by Professor Reed.

A finite number of applications of the operations of addition and multiplication of matrices will, of course, yield only polynomials, but Pipes in his remarkable paper shows the practical value of considering an infinite number of applications of these operations, as in a power series, thus arriving at the notion of more general functions of matrices. Then the beautiful, powerful, but little-known Cayley-Hamilton Theorem shows that these general functions of a matrix are not nearly as complicated as one might first expect, but reduce to simple sums of these functions of the latent roots of the matrix with easily expressed matrix coefficients.

I believe that this is the first time that the Cayley-Hamilton Theorem has appeared in ELECTRICAL ENGINEERING. Pipes is to be highly commended for calling this powerful tool to the attention of electrical engineers, particularly as he gets down to brass tacks in his remarkable paper, and for several well chosen examples, shows how by proper use of this theorem, numerical results are quickly and easily reached. I hope this paper will receive the wide and careful attention it deserves, and that it will stimulate the further proper application of higher mathematics to electrical engineering problems.

Louis A. Pipes: Doctor Slepian summarizes the utility and power of matrix algebra in the usual engineering problem leading to a discussion of linear dynamical system in a most concise and comprehensive manner.

There appears to be some confusion among some engineers concerning the relation of matrix algebra to tensor algebra. It should be realized that a matrix may be regarded as a tensor of the second rank with respect to a linear transformation. Since practically all the equations met in practical engineering problems are linear, linear transformations are encountered and consequently the summation convention, upper and lower indices, and other tensor machinery may be dispensed with and the classical matrix notation employed.

Matrix theory has received a great deal of attention by the mathematicians and many powerful theorems exist in the mathematical literature which have great practical importance. By the use of these theorems, the solution of polynomial equations, the calculation of normal modes, and other processes of great importance in engineering and physics may be most easily accomplished.

In conclusion, it should be pointed out that on page 1178 of the paper "Matrices in Engineering" the last word in section *D* should be "commutative" and not "symmetric."

The Properties of Three-Phase Systems Deduced With the Aid of Matrices

Discussion and author's closure of a paper by M. B. Reed published on pages 74–7 of this volume (February section), and presented for oral discussion at the basic sciences session of the winter convention, New York, N. Y., January 26, 1938.

Joseph Slepian: For discussion, see this page.

Irven Travis (University of Pennsylvania, Philadelphia): I agree most heartily with Mr. Reed that the matrix formulation of electric circuit problems clears away the algebraic debris and thus more clearly reveals the main line of reasoning. Mr. Reed has given a number of very interesting examples.

There is one point which I should like to amplify. Below equation 39 is the statement, "This equation cannot be used to determine E_{pg} in terms of I_{pg} because of the singularity of the transformation. Further investigation will show that no relation can be found for E_{pg} in terms of I_{pg}, and the circuit impedances or admittances; i.e., given a set of wye-connected impedances and the line currents, the phase generator voltages of the source cannot be computed." Although it is true that there are infinitely many voltages which will satisfy the system, valuable information can be obtained by transforming equation 39 to symmetrical co-ordinates.

Let the matrix S be defined as

$$S = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \qquad (1)$$

where

$$a = \epsilon^{j\frac{2\pi}{3}}$$

Multiplying both sides of equation 39 by S and inserting $S \cdot S^{-1} =$

U_1 in the product on the right hand side, we have

$$(SI_{pq}) = (ST_yYT_YS^{-1})(SE_{pq}) \tag{2}$$

By expanding (SI_{pq}) and (SE_{pq}) it is easy to see that

$$SI_{pq} = (I_{A10}, I_{A11}, I_{A12}) \tag{3}$$

$$SE_{pq} = (E_{100}, E_{101}, E_{102}) \tag{4}$$

in which the added subscript (0, 1, 2) denotes a zero-, positive- or negative-sequence quantity.

Let Y, which is the inverse of 32, be denoted by

$$Y = \begin{pmatrix} y_{11} & y_{12} \\ y_{12} & y_{22} \end{pmatrix} \tag{5}$$

then the product on the right hand side of equation 2 is

$$ST_yYT_YS^{-1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{11} - y_{12} + y_{22} & -(ay_{11} + 2a^2y_{12} + y_{22}) \\ 0 & -(a^2y_{11} + 2ay_{12} + y_{22}) & y_{11} - y_{12} + y_{22} \end{pmatrix}$$

Equation 2 is therefore of the form

$$I'_{pq} = Y'E'_{pq} \tag{6}$$

where

$$I'_{pq} = (I_{A11}, I_{A12}) \tag{7}$$

$$E'_{pq} = (E_{101}, E_{102}) \tag{8}$$

$$Y' = \begin{pmatrix} (y_{11} - y_{12} + y_{22}) & -(ay_{11} + 2a^2y_{12} + y_{22}) \\ -(a^2y_{11} + 2ay_{12} + y_{22}) & (y_{11} - y_{12} + y_{22}) \end{pmatrix} \tag{9}$$

The matrix Y' is not singular, hence it is possible to express the positive- and negative-sequence components of the generator phase voltages in terms of the phase currents and the circuit impedances. Thus the phase voltages are arbitrary because their zero-sequence components are arbitrary, but they cannot be assigned any values at random as might be inferred from the statement below equation 39.

M. B. Reed: As Mr. Travis points out, the generator phase voltages of a wye system are arbitrary only through the arbitrariness of the zero-sequence component of these voltages. This voltage component may have any one of a doubly-infinite set of values—any one of an infinite set of lengths, for a particular position or any one of an infinite set of positions for a particular length—and still the phase voltages will give the same set of line voltages. This result can be readily shown without recourse to symmetrical components as follows:

If the point at the center of gravity *cg* of the line-voltage triangle is designed by *o'*

$$\mathfrak{E}_{Lg} = \mathfrak{U}_{12}\mathfrak{E}'_{pg} = \mathfrak{U}_{12}(E_{10'}, E_{20'}, E_{30'}). \tag{1}$$

Since $\mathfrak{U}_{12}$ is singular, this transformation is irreversible. However, if the relation

$$E_{10'} + E_{20'} + E_{30'} = 0$$

is used to eliminate $E_{30'}$ from the first two of the equations represented by (1), and if the third equation is omitted, the result is

$$\mathfrak{E} = \begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix}(E_{10'}, E_{20'}) = \begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix}\mathfrak{E}' \tag{2}$$

and since the transformation matrix is nonsingular

$$\mathfrak{E}' = \frac{1}{3}\begin{pmatrix} 2 & 1 \\ -1 & 1 \end{pmatrix}\mathfrak{E} \tag{3}$$

i.e., the voltages to the *cg* of the line-voltage triangle determine the line voltages. But from the fact that

$$\mathfrak{I} = \mathfrak{Y}\mathfrak{E} = \mathfrak{Y}\begin{pmatrix} 1 & -1 \\ 1 & 2 \end{pmatrix}\mathfrak{E}' \tag{4}$$

evidently the currents are completely determined from the voltages to the *cg* of the line-voltage triangle. Further since

$$\mathfrak{E}_{pg} = \mathfrak{E}'_{pg} + E_{o'o}(1,1,1) \tag{5}$$

it is evident that $E_{o'o}$, the voltage between the common point *o* of the generator and the *cg* of the line-voltage triangle, is the arbitrary element in the phase voltages of the generator, and further that $E_{o'o}$ has no effect on the currents in the system no matter what its value.

Corona Voltages of Typical Transformer Insulations Under Oil

Discussion and author's closure of a paper by F. J. Vogel published on pages 34–6 of this volume (January section), and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

I. W. Gross: For discussion, see page 194 of this volume (April section).

V. M. Montsinger (General Electric Company, Pittsfield, Mass.): Mr. Vogel's paper is of considerable interest to me as it deals with a subject along my line of work.

I wish to discuss it from several viewpoints.

Mr. Vogel's experience with the harmful effects of air in his barrier parallels closely my own experience. As stated in my paper I found that any air at all in the structure gave misleading results and I found it necessary to assemble the sample under oil, not allowing the small coil used as the line electrode to come in contact with air after vacuum treatment and oil impregnation.

I subscribe 100 per cent to his second conclusion in that it is very important to remove all entrapped air in transformers before making commercial tests at the factory. Also if high-voltage transformers are not shipped filled with oil or are untanked for inspection, special means should be taken to remove the air. If a vacuum cannot be applied, one of the best means of getting the air out is to make a short-circuit heat run. Laboratory tests have shown that if oil is circulated by an air pocket it takes only a few hours to absorb the air. Tipping the transformer often is helpful in removing air pockets that are not adjacent to the oil in circulation.

I note that Mr. Vogel obtained an impulse ratio in the order of 2 to 2.3. My own tests do not bear this out. I have found that the ratio varies over a much wider range, depending on the construction of the sample. Based on the tests given in my paper and on the injurious corona voltage, I found a ratio of 1.75 for barrier *C* and 2.48 for barrier *D*. Barrier *C* had a spacing of 0.641 inch from the coil to ground and *D* a spacing of 2.5 inches from the coil to ground. I cannot agree, therefore, that there is a constant impulse ratio for all voltage ratings of transformers.

Mr. Vogel's statement that the dielectric strength varies approximately as the barrier thickness raised to the two-thirds power checks my experience. I have used this two-thirds-power rule for several years. I have found that the dielectric strength of oil when tested with edged electrodes or with round rods varies with the spacing raised to the two-thirds power. However, if tested in a uniform dielectric field it varies more nearly in proportion to the spacing. I believe that cable engineers have found that the strength of the paper covering varies approximately as the thickness. While cable insulation is stressed highest next to the bare part of the cable on account of its reduced periphery, the conditions are such that it corresponds fairly well with a uniform field. That is, there are no sharp corners or edges to cause voltage concentrations.

I believe it can be said, therefore, that the two-thirds-power law is

not inherent in the characteristics of the material—solid or oil—but by the shape of the electrodes.

Conditions in transformers are such that most all insulations are in nonuniform fields and on this account we must generally increase the insulations faster than the test kilovolts. Roughly speaking, by the two-thirds rule, if the test is doubled, the distance or insulation must be trebled. This explains why the cost and size of transformers increases so fast with voltage.

L. H. Hill (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): It is interesting to note from Mr. Vogel's paper that as a result of his impulse tests he has reached the conclusion that transformers should be filled with oil under a vacuum.

The company with which I am associated has been filling high-voltage transformers with oil under a vacuum for about five years, and repeated tests have indicated the desirability of going to that extra trouble. In connection with filling transformers under vacuum, we have found that the method of filling the transformer tanks with oil has considerable bearing on the amount of time required to do this. If the transformer tank is filled from the bottom, we have found that it may take as long as four days for the surplus air to come out of the oil; however, if the transformer tank is filled by running the oil in at the top so that the oil goes into the transformer as a foam, by the time the transformer tank has been filled, the oil is perfectly quiet, indicating that all the air has been removed.

From a practical point of view, the increased cost of building transformer tanks so that oil could be installed in the field with the tanks under a vacuum would not be very great.

Eric A. Walker (Tufts College, Mass.): Mr. Vogel, in his paper, has undoubtedly opened a field which may well help us to discover more of the factors which lead to the breakdown of fibrous insulation under oil.

In this paper Mr. Vogel mentions the detection of corona by audible frequencies only, that is, directly by ear or by the use of a microphone.

There are at least three methods by which corona may be detected. An audible method as described by Mr. Vogel makes use of the energy in a limited frequency range. A radio-frequency detector and amplifier, used in the radio- and intermediate-frequency ranges, has met with some success. One can also find the corona voltage by power-factor measurements and ascertaining the point at which there is an abrupt rise in power factor. In a recent investigation, in which the three methods were compared, the power-factor method showed a lower critical voltage than the other two methods. In another investigation, on a system of concentric electrodes separated by several layers of fibrous insulation, it was possible to detect when each layer of occluded air became ionized by a sudden increase in power factor. Of course such a method would not give a definite point on a large transformer unless the corona became quite general.

The second consideration in this paper is its effect on operating practices. It is recognized that the first few days during which a transformer is energized are critical ones. This is probably more true of transformers which have served some time as spare transformers than of new ones. Failures during this critical period have usually been attributed to the absorption of moisture by the fibrous insulation. Although evidence indicates that the insulation does absorb moisture by breathing there is no proof that moisture alone is the only cause or even the principal cause of deterioration. Now Mr. Vogel points out that occluded gases may lower the corona voltage. This will cause "tracking" which would not take place if the gas were not present as is usually true in normal operation. This type of deterioration may well be more serious than the absorption of moisture for the damage caused by such carbonization is permanent and cannot be remedied as the absorption of moisture can be by a mere drying process.

Ultimately it will be desirable to detect the formation of corona in transformers in service, both during normal operation and during overvoltage tests. It is extremely doubtful if aural methods would be sufficient for such tests. Radio-frequency tests are difficult to use because of the normal corona in substations. A power factor test would have a wide application as a field test where the moisture content of the insulation is important as well as the voltage at which corona is initiated. Such a test also has the advantage of being a nondestructive test if applied at, or below, the operating voltage.

J. O. Fenwick (Line Material Company, South Milwaukee, Wis.): Mr. Vogel's paper on "Corona and Oil-Impregnated Insulation" describes one of several lines of investigations now being pursued in the improvement of transformer insulation, particularly against lightning surges. Elaborate studies, such as outlined in this paper, are ordinarily considered as being confined to large power transformers, but similar investigations are now being adopted in the development of distribution transformers as well. Such studies are of particular value in the design of rural-type transformers where exposure to lightning is severe and protection is not of the best. Other parallel lines of investigation on insulation are studies of power factor of the insulation, radio interference, as well as the more familiar puncture tests on 60-cycle and impulse voltages.

The corona test described by Mr. Vogel as well as the radio-noise and power-factor studies give valuable information not shown by the more conventional puncture tests. For one thing, this specimen under test need not be totally destroyed as is frequently the case with puncture tests and yet the voltage can be raised to the point at which the insulation begins to show signs of distress as manifested by the corona markings mentioned by Mr. Vogel, or by radio noise where this is used as an indication of corona. Very often a better picture of the electrostatic field is obtained and corrected measures can be applied more intelligently than is the case where the test specimen is totally destroyed.

Another result is that since corona is one of the first immediate indications of over-stressed insulation, the corona voltage is somewhat analogous to the "yield point" of a metal specimen with mechanical loading and the value of this information to the designer is obvious.

The point not emphasized by Mr. Vogel is the uncertainty of results and limited conclusions that can be drawn unless a great amount of test data is accumulated. The voltage resulting in corona and ultimate puncture of the specimen depends so much upon the shape of the electrodes, presence of sharp corners, and other such incidental factors that a seemingly comprehensive test often gives results which are rendered nearly valueless when some apparently minor change is made in the method of test. For this reason, tests made with electrodes and specimens which appear to simulate conditions in the actual transformer often give misleading results as far as numerical design data is concerned, and a large amount of testing must be done in order to obtain even a moderate amount of reliable and usable information.

The seeming inconsistency of the results of insulation studies is illustrated by a comparison of the results reported by Mr. Vogel and others obtained by our own company. Mr. Vogel reports a ratio of roughly two to one between impulse puncture and 60-cycle corona voltage. Our own tests on samples of insulation and also assembled transformers indicate that this ratio, instead of being two to one as reported by Mr. Vogel, for well-impregnated specimens, may vary as much as ten to one, for certain peculiar conditions of test. Our results do emphasize, however, the importance of thorough impregnation and the necessity for eliminating air from the test specimen if consistent results are to be obtained. The results are of considerable value in giving the designer a "feel" of the distribution of the electrostatic field, but as indicated in the foregoing, the numerical results must be used with considerable caution.

F. J. Vogel: I was greatly interested in Mr. Montsinger's discussion, inasmuch as he found that the air entrapped in insulation structures caused them to give erratic results, and in his agreement with me that it was important to remove all entrapped air in transformers before making commercial tests at the factory. It is my opinion, based on our tests, that higher values can be obtained by vacuum filling than by removing air in any other way. Our own ex-

perience has been that transformers in service as long as a year and a half may still have entrapped air which can result in a failure. Therefore, vacuum filling would seem to be essential even in the field if maximum dielectric strength and certainty were to be obtained.

I agree with Mr. Montsinger that it is possible to obtain impulse ratios over quite a range. However, I have tried to be careful to limit the application of the 2.2 ratio to a specific type of construction. My paper covered only barriers with interleaved insulation. Depending upon the interpretation of Mr. Montsinger's data for barrier D, somewhat lower values than 2.48 might be given. I have tried to be conservative in this to furnish values which could be expected rather than the maximum values. Barrier C is not of the same construction and, as stated in my discussion of his paper, I do not believe that his construction is typical of any insulation structure actually used in a transformer.

With relation to the dielectric strength of oil in uniform fields, or in fields due to edged electrodes or round rods, it is interesting to note Mr. Montsinger's findings, and I believe this is a subject which is worthy of a future paper.

The future of power-factor tests on transformers is uncertain in the writer's opinion. Data which we have to date indicate that corona even in service is unlikely. To detect corona by power-factor measurements with present-day equipment seems impossible.

The question of using voltage measurements and times only, instead of gap lengths for specifications and test purposes, seems to be evading the issue. One organization of consulting engineers specifies gaps to be installed at the terminals of their transformers. They specify that a voltage wave of given steepness be impressed upon the transformer to prove the transformer will withstand this condition. The purpose of this test undoubtedly is to prove that the transformer with the gap installed in service will be protected against failure of the transformer windings. If voltage data from one source is used to specify the voltage to be applied, and the tests on the unit are not made in the laboratory where these readings agree, it might be possible to obtain a transformer which would not withstand the operating conditions desired by the purchaser. It seems to the writer that it is better to use a direct method of test rather than to use an intermediate step where there is a possibility of error.

I believe that the previous discussions show clearly that it is possible to increase the impulse strength of commercially oil-insulated transformers by admitting the oil to the tank while the winding is still under vacuum. It should be possible to do this in the field and, with special equipment filtering the oil, should be possible without even a temporary reduction in impulse strength from transferring the oil. The per cent increase in strength, due to vacuum-filling, as compared to nonvacuum filling, is variable.

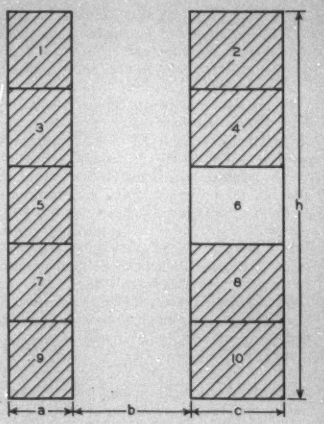
A Formula for the Reactance of the Interleaved Component of Transformers

Discussion and authors' closures of a paper by H. B. Dwight and L. S. Dzung published on pages 1368–71 of volume 56, 1937, AIEE TRANSACTIONS (November 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the electrical machinery session of the winter convention, New York, N. Y., January 27, 1938.

A. N. Garin (General Electric Company, Pittsfield, Mass.): A theoretically rigorous solution of the problem of transformer reactance presents many difficulties due to the complexity of the physical structure of transformers. The factors chiefly responsible for these difficulties are: the curvature of windings, the presence of core iron, and the nonuniformity in the turn distribution in the cross section of windings. A practical engineering solution consists, therefore, first, of idealizing the structure until it is amenable to calculation by one of the theoretical methods available; second, of selecting the theoretical method best suited for the purpose and of performing the calculation; and third, of applying to the result of the theoretical calculation, whenever necessary, an empirical correction factor, which should not exceed a few per cent of the calculated value. Thus, calculation of reactance for a modern complicated transformer is not science, but an art, based on science.

The present trend in transformer design naturally results in a race between the growing complexity of windings and the increasing skill of the reactance calculator. The reactance calculator usually

Figure 1. Cross section of windings



wins the race, and when he does not, he can use a reduced scale model of the transformer to be built and obtain the reactance by test, as described in a recent AIEE paper,[1] a procedure which may save time, and incidentally a professional reputation.

Mr. H. O. Stephens' method of resolving the reactance of nonuniform concentric windings into the concentric and interleaved components is a definite milestone in the art of reactance calculation and Messrs. H. B. Dwight and L. S. Dzung are to be congratulated on the very clear presentation, in the first part of their paper, of the physical phenomena justifying this method. At the risk of being accused of pedantry, I should like to call their attention, however, to an obvious oversight in their statement that I^2X is stored energy and is equal to the summation of $H^2/8\pi$. Being power, and not energy, I^2X cannot possibly be equal, but is proportional, to the summation of $H^2/8\pi$.

Having resolved the reactance of the transformer into its concentric and interleaved components, the next step is to select suitable formulas for calculating the two components separately. For the concentric component Dwight and Dzung use the well-known expression given by their equation 1. It will be observed that this formula does not take into account the curvature of windings and the presence of core iron, moreover, it assumes the effective axial length of windings to be equal to their physical length. The last two factors introduce errors of opposite signs, partly compensating one for the other, so that, as stated by the authors, the formula may be quite accurate, but only for a certain range of dimensions and proportions of the core and the windings.

For the interleaved component Dwight and Dzung use a formula based on the theory of geometric mean distances. The effects of curvature and of iron are again neglected. The reactance in question can be calculated with equal or greater ease, and with all the accuracy required for the purpose, by older and better known methods, of which that due to Rogowski[2] is perhaps the most advanced. The principal value of the second part of this paper is, therefore, in my opinion, not in the solution of this particular interleaved reactance but in the relative novelty of the method of attack. Although a rather complete study of the application of geometric

mean distances to calculation of transformer reactances was published several years ago in German,[1] American technical literature seems to have neglected the subject.

Since the effect of curvature has been neglected in this paper in calculating both the concentric and the interleaved reactances, nothing would be sacrificed by performing the complete reactance calculation in terms of geometric mean distances. Figure 1 of this discussion represents the windings of the transformer investigated in the paper. Each winding is shown subdivided into five equal blocks. When operating on the 11,000-volt connection block 6 is idle.

Primary-to-secondary reactance of a transformer is given, in terms of geometric mean distances, by the following formula:

$$X_{P-S} = K \log \frac{R^2_{P-S}}{R_{P-P} R_{S-S}} \tag{1}$$

where

X_{P-S} = primary-to-secondary reactance
K = coefficient depending on frequency, the length of mean turn, the base of the log, and the choice of units
R = geometric mean distance between areas indicated by subscripts

For the present case the primary consists of blocks 1, 3, 5, 7, 9, the secondary of blocks 2, 4, 8, 10, so that equation 1 becomes:

$$X_{13579-24810} = K \log \frac{R^2_{13579-24810}}{R_{13579-13579}\, R_{24810-24810}}$$

$$= K \log \frac{R^{2\text{-}5}_{13579-246810}\; R^{0\text{-}4}_{13-24}}{R^{0\text{-}9}_{379-6810} R_{13579-13579} R^{0\text{-}5}_{24-24} R^{0\text{-}5}_{24-6\text{-}10}} \tag{2}$$

Equation 2 contains only geometric mean distances between rectangles and from rectangles to themselves, all of which can be calculated by the method described in the paper. The point of particular interest in this solution is that the final reactance has been obtained directly, without resolving it into concentric and interleaved components.

If it is desired to retain the resolution of reactance into concentric and interleaved components, the concentric component can be readily calculated as follows. Let the primary, consisting of blocks 1, 3, 5, 7, 9, be called A and the secondary, consisting of blocks 2, 4, 6, 8, 10, be called C, so that equation 2 becomes:

$$X_{A-C} = K \log \frac{R^2_{A-C}}{R_{A-A}\, R_{C-C}} \tag{3}$$

Following the method described in the appendix to the paper and denoting the space between A and C by B:

$$X_{A-C} = K \log \left[\frac{R^{\frac{(a+b+c)^2}{abc}}_{ABC-ABC}\; R^{\frac{b^2}{ac}}_{B-B}}{R^{\frac{(a+b)^2}{ac}}_{AB-AB}\; R^{\frac{(b+c)^2}{ac}}_{BC-BC}\; R_{A-A}\; R_{C-C}} \right] \tag{4}$$

Finally, using natural logs and expressing geometric mean distances in terms of semiperimeters, equation 4 can be replaced by the approximate expression:

$$X_{A-C} = K_1 \left[\frac{\frac{a}{3} + b + \frac{c}{3}}{h} - \left(\frac{\frac{a}{2} + b + \frac{c}{2}}{h} \right)^2 \right] \tag{5}$$

For a wide range of proportions the approximate expression (5) gives a value within two per cent of the exact expression (4).

An interesting side light on H. O. Stephens' method may be obtained by substituting algebraically the values of concentric and interleaved reactances in terms of geometric mean distances, the former being given by equation 4, into the H. O. Stephens' formula:

$$X_{13579-24810} = X_{13579-246810} + \frac{1}{25} X_{24810-6} \tag{6}$$

If equation 6 were exact the result of this substitution would be equation 2. Actually, however, although a very close approximation, equation 6 is not exact. The exact formula is:

$$X_{13579-24810} = X_{13572-246810} + \frac{1}{20}(5X_{13579-246810} - 9X_{135-246} + 4X_{13-24}) +$$
$$\frac{1}{25} X_{24810-6} + \frac{1}{100}(X_{2-4} + 2X_{2-6} - 2X_{2-8} -$$
$$X_{2-10} - X_{1-3} - 2X_{1-5} + 2X_{1-7} + X_{1-9}) \tag{7}$$

Considering the difficulty of obtaining accurate reactance by tests on a model of the size described in the paper, the agreement between calculated and test values is satisfactory, even if inconclusive. It is regrettable, however, that the authors do not state whether in making their tests without an iron core they had the primary and secondary windings of equal turns and connected in series opposition, thus obtaining

$$X_{1-2} = \omega(L_1 + L_2 - 2M_{1-2}) \tag{8}$$

corresponding to the basis of their calculation. If in their tests they had the secondary short-circuited they were measuring:

$$X_{1-2} = \omega\left(L_1 - \frac{M^2_{1-2}}{L_2}\right) \tag{9}$$

Although (8) and (9) are practically identical for an iron core transformer, they may be radically different for an air core transformer.

References

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2. Mitteilungen ueber Forschungsarbeiten, W. Rogowski, 1909.
3. Weitere Entwicklung der allgemeinen Methode zur Berechnung der Streuung von Transformatoren, G. Petrow. *Electrotechnik und Maschinenbau*, 1934.

H. B. Dwight: In connection with the interesting discussion by A. N. Garin, a distinction may be made between expressions which are so long as to be of merely academic interest, and formulas which are concise enough to be of practical use. For instance, equation 2 of the discussion contains four geometric mean distances of one rectangle from another, and if these are to be calculated by the method described in the paper, each would give rise to several self geometric mean distances, making 13 self geometric mean distances for the formula. But equation 2 of the paper gives the reactance with only four self geometric mean distances, and so is not unduly long.

The observation is correct that I^2X is proportional to stored energy, not equal to it. The coils in the model ironless transformer had a turn ratio of one to one and were connected in series. The secondary was not short-circuited.

In the thesis work upon which the paper is based, the self- and mutual inductances were calculated, as a check, by formulas for cylindrical coils. This brought the curvature of the conductors into the calculation but not the effect of the iron core. It seems probable that such long calculations will not be practical for routine computations in designing. The need at the present time appears to be a comparison of the results of the shorter calculations with measurements on a number of practical transformers whose dimensions have been accurately found, so that the percentage error to be expected from a given calculation may be known.

L. S. Dzung: Rogowski's method of attacking the problem of reactance of interleaved transformer windings, as mentioned in Mr. A. N. Garin's interesting discussion, is very general in character; but the restriction[1] on dimension ratios of his approximate formula[2] limits its application more suitable to the calculation of the reactance of an interleaved transformer rather than to that of the interleaved component of a transformer. The coil shape of the former is usually such that the axial height is small compared to the radial depth. This condition is seldom realized in the case of the inter-

leaved component of a transformer. His more exact formula[3] is too lengthy to be applied in practical designing.

It may be noted that the curves on figure 2 of the paper and the little formula printed beside offer a very simple means to a practical designer. Equation 2 of the paper and also equation 2 and equation 4 of Garin's discussion have the disadvantage that they involve obtaining a small number from the difference between large numbers. In preparing the curves logarithms have been taken to a sufficient number of significant figures so that the final results will give engineering accuracy.

Equation 4 of Garin's discussion, which is equation 9 of G. Petrow's paper in *Elektrotechnik und Maschinenbau*, 1934, has been used in the thesis to compare the reactance of the concentric component as calculated by the geometric-mean-distance method against that by the formulae for cylindrical coils and by the usual formula, equation 1 of this paper. The results of these three calculations are respectively 5.30 per cent, 5.31 per cent, and 6.21 per cent for the transformer given in example II of the paper.

The effect of the iron core can be taken care of by the method of image as indicated also in Petrow's paper. A comparison between equation 21′ and equation 23 of Rogowski's paper shows that this effect would not be very great

References

1. **W. Rogowski,** *Mitteilungen ueber Forschungsarbeiten*. Heft 71 (1909). Abs. II, §3, 2.
2. **W. Rogowski,** ibid., equation 23.
3. **W. Rogowski,** ibid., equations 13 and 14.

Oil Oxidation in Impregnated Paper

Discussion and authors' closure of a paper by J. B. Whitehead and T. B. Jones published on pages 1492–1501 of volume 56, 1937, AIEE TRANSACTIONS (December 1937 issue of ELECTRICAL ENGINEERING) and presented for oral discussion at the cables and research session of the winter convention, New York, N. Y., January 27, 1938.

L. E. Fogg and **R. B. Power** (Kennecott Wire and Cable Company, Phillipsdale, R. I.): About eight or ten years ago the research department of our company attempted some electrical tests on samples quite similar to those used by the authors. The results of this work were very unsatisfactory because of the nonuniform shrinkage of the paper samples. During the drying process, bulges and swills were formed in the samples to such an extent that the upper electrode was appreciably raised, even though its weight was sufficient to produce a pressure of several pounds per square inch on the sample. We would be interested to know if the authors encountered any such difficulty in their work, and how they were able to avoid it.

In connection with figure 7 of the paper, the authors suggested that a cause of the rising power factor—voltage characteristic might be the formation of some ions through atomic or electronic collisions. It is not obvious why such a factor should permit later flattening of the curves as still higher voltage stresses are applied, unless it may be assumed that there are but a limited number of atoms susceptible to such ionization. We would appreciate hearing the authors' viewpoint on this phase of the subject.

There is an apparent discrepancy in figures 22 and 23. The authors attribute to incomplete saturation both the low capacitance of figure 22 with respect to the comparable oxygen treated sample, and the initial decrease of the ionization curve of figure 23. However, this decrease apparently is brought about by more complete saturation, which at the same time should bring about an increase in the capacitance of figure 22, which increase is conspicuously absent.

The catalytic effect of metals on oxidation as well as deterioration of the oil in the absence of oxygen has been referred to at several points in the paper. However, data has been given only for brass. It seems that similar data for the metals, which the cable saturant must contact, would be of greater interest and value. We would appreciate such data as the authors might be able to supply for such metals as copper, lead, tin, and iron.

The conclusions drawn by the authors upon the effects of oxidation cannot be applied to cable practice without further investigations. All the work has been done for relatively short time intervals: 192 hours is, after all, but a brief period in the expected life of a power cable. Almost none of the curves has approached a constant value of power factor in this length of time. It seems safe to assume that these curves will continue to rise for a much longer period of time, eventually, perhaps, to a value so high that successful cable operation might be impaired. It also seems possible that there may be some further later reaction of the oxidized products with themselves or with fresh oil, which may cause a more rapid increase of power factor. Certainly, definite conclusions should not be reached until the results of the authors have been substantiated by long time tests.

Moreover, these tests have been made under constant conditions of temperature and pressure, tending to discourage any movement of the oil through the samples. If the samples were subjected to load cycles similar to those of an operating cable, so that there would be an oil migration, permitting the oxidized products to encounter fresh oil, an entirely different set of results might be obtained.

We hope that Professor Whitehead will continue his work on this phase of cable saturants, so that these factors of time and oil migration may be considered.

L. J. Berberich (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The result reported by the authors that small amounts of oxygen had practically no effect on the electrical properties of the one oil studied throws new light on the oxidation problem of cable oils. Unfortunately, however, in order to generalize this result, a range of oils of different constitution must be studied. The authors give very little information which would enable one to obtain an idea of the constitution of the oil except for the broad statement that the oil is a "highly refined paraffinic cable oil." While there is no accurate way of characterizing the constitution of oil, it has, nevertheless, been found that the "viscosity index" is of value in this connection. This leads the writer to suggest that more use should be made of this index by those studying insulating oils.

The term "viscosity index" and its use as a constitutive property of the oil was first proposed by Dean and Davis (*Chem. and Met. Eng.*, volume 36, page 619, 1929). It is independent of the value of the viscosity and permits the expression of the viscosity-temperature coefficient of the oil as a simple function of the Saybolt universal viscosities at 100 and 210 degrees Fahrenheit. The system was devised on the basis that a typical coastal oil is taken to have a viscosity index of zero and a typical Pennsylvania oil is taken to have one of 100. From empirically derived equations connecting the viscosities at 100 and 210 degrees Fahrenheit for oils from these two extremes of crudes, Dean and Davis compute data for a table. Knowing the viscosities at 100 and 210 degrees Fahrenheit, use of this table and a simple arithmetic calculation will give the viscosity index.

A number of interesting correlations of viscosity index with other properties of insulating oils have already been made. Sommerman (ELECTRICAL ENGINEERING, volume 56, page 566, 1937) has found that the amount of *x*-wax formed by cable oils when subjected to gaseous ionization increase with increase in viscosity index of the oil. Balsbaugh, Larsen and Oncley (1937 Report on Research Project on Electrical Insulating Oils at MIT sponsored by Utilities Coordinated Research, Inc.) have found at least an approximate relationship between ease of oxidation and viscosity index among a group of oils representing extremely wide variations in constitution. Viscosity index heads the list of physical constitutive properties which these workers suggest as useful for predicting chemical behavior. The writer also, in his work on cable oils, whether it was a study of stability to oxidation or stability to gaseous ionization, has

found the use of viscosity index valuable. Hence, with this much evidence in favor of viscosity index, the writer believes this work of the authors could be better correlated with that of others if the viscosity index had been given.

G. M. L. Sommerman (American Steel and Wire Company, Worcester, Mass.): From the physical properties of the oil given in table II by Whitehead and Jones, it is calculated that the specific gravity of the oil at 60 degrees Fahrenheit is $G = 0.918$ and the viscosity at 100 degrees Fahrenheit is $V = 2{,}360$ Saybolt seconds. These data may be used to calculate the viscosity-gravity constant of the oil according to the method proposed by J. B. Hill and H. B. Coats (*J. Ind. and Eng. Chem.*, volume 20, 1928, page 641), which is as follows:

$$a = \frac{10\,G - 1.0752 \log(V - 38)}{10 - \log(V - 38)}$$

For the oil in question, $a = 0.84$; for highly paraffinic oils, $a = 0.80$; for highly naphthenic oils, $a = 0.87$. This indicates that the oil is probably of midcontinent source with a viscosity index in the neighborhood of 70. It would be of interest to have oxidation data of the kind presented by Whitehead and Jones for the other types of oils.

From the data presented in this paper it is not clearly proved that the *process* of oxidation in oil (as distinct from the results of oxidation) is a source of increased power factor. First, the decrease in power factor following the degassing of aged oil may be due to the removal of volatile oxidation products, as recognized by the authors. Second, the higher "ionization factors" of the undegassed samples compared with those of the degassed ones may also be due to volatile constituents. Third, the greater rate of rise of power factor with increase in temperature for specimens containing more oxygen may be due simply to the higher power factors of the more highly oxidized oils. Power factor-temperature curves of impregnated paper similar to the authors' figure 18 were reported by the writer in a recent paper (ELECTRICAL ENGINEERING, volume 56, 1937, page 566, figure 6). Rapidly rising power factor-temperature curves were obtained when the saturants were *degassed* deteriorated oils, and the values were practically independent of time, at least up to 24 hours. This is also in accordance with the results reported earlier by Whitehead (AIEE TRANSACTIONS, volume 52, 1933, page 667).

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): We in Chicago have been making tests on 1,000-foot lengths of experimental 132-kv cable and have obtained some test data on the effects of small amounts of dissolved oxygen or air on the characteristics of oil-filled cable insulation. Apparently during either manufacture or installation a slight amount of air was entrapped in some of these cables. After these cables had been subjected to heating cycles to about 70 degrees centigrade for 10 or 20 days, measurements of power factor at 60 degrees centigrade showed no change at all from the measurements obtained when the cables were first installed. In one cable the effects of the entrapped air required one month to show increases in power factors at 60 degrees centigrade, while for the other cable a few years were required.

From this experience and other considerations, I am forced to disagree with the conclusion of Whitehead and Jones on the relative unimportance of small amounts of oxygen as affecting electrical properties. Tests on this point apparently require more than the seven days used by them.

One of the outstanding characteristics of the deteriorated experimental cables in Chicago was the development of so-called negative ionization factors. The authors' tests obviously did not last long enough to develop negative ionization factors.

It is of interest to note that the ionization factors reported by the author decreased "when oxygen and volatile products were withdrawn." This fact seems to indicate that some gaseous ionization was present, and such a conclusion is supported by the test results with nitrogen.

The radial power-factor tests were made at room temperature. We have found that samples which show interesting variations in power factor when tested at 60 degrees centigrade show in some cases insignificant variations at room temperature.

One of the helpful results of the authors' studies is that, in testing stressed oil, it is better not to remove moisture and volatile products in order to retain reliable indications of the condition of the stressed oil.

J. B. Whitehead and T. B. Jones: We are in agreement with the suggestion of Doctor L. J. Berberich that it would be desirable to correlate all studies of the electrical properties of oils with the respective values of the viscosity index. In the case of the oil used in our studies, we did not determine the viscosity index, nor was it furnished with other properties of the oil as given by the refiner, as set forth in table 2. We note, however, that Doctor Sommerman in his discussion has estimated the value of the viscosity index to be in the neighborhood of 70.

Mr. Wyatt raises the question of the influence of a longer period of test on variations of layer power factor due to oxidation. We agree with him that longer tests would probably accentuate layer variations of power factor. However, our results indicate that the U-shaped curves sometimes observed in new cables are probably not due to oxidation. Furthermore, we have given evidence of a quantitative evaluation of the amount of oxygen necessary to produce a layer effect within a limited time.

Replying to Messrs. Fogg and Power, we encountered no instances of buckling or nonuniform shrinkage in our samples. Throughout our tests a constant weight was kept on the upper electrode. This was done to maintain uniform pressure throughout the test. Apparently this weight was sufficient to prevent troubles of the nature mentioned. A rising power factor-voltage characteristic passing through a maximum, and followed by a descending portion has often been noted in our work. An explanation has been offered in the paper "Residual Air and Moisture in Impregnated Paper Insulation—II" (Whitehead, Kouwenhoven, and Hamburger, AIEE TRANSACTIONS, volume 47, 1928). The conductivity and the number of ions in the oil have relatively low values. With increasing stress collision ionization is possible, but is not cumulative, owing to the limited length of path. Above a certain stress all of the free ions, including those caused by ionization, pass to the limits of their free paths in both positive and negative half cycles. A saturation condition results, the power factor passes through a maximum, and with further increase of voltage, conduction current is constant and capacitance current increases, causing a decrease in power factor. This picture is a suggestion only. An alternative one for the rising power factor at lower stresses is that with increasing stress large molecular aggregates surrounding the ions are stripped of their outer envelopes of neutral molecules, acquire higher velocities with resulting increased conductivity. The curves of figure 21 indicate that with increasing temperature both of these effects may be involved.

The apparent inconsistency between the power factor-voltage and power factor-time curves for nitrogen and for air is due to the difference in pressure (gas content) between the two tests. The nitrogen test was at ten centimeters and air test at one millimeter pressure. Thus in the nitrogen sample there was 100 times as much gas as in the air sample. Thus capacitance changes in the latter were too small to be detected. In this connection, it is worth noting that the constant value of capacitance of the air sample is between five per cent and ten per cent less than that of the one-millimeter oxygen sample, thus indicating a better impregnation for the latter.

We are glad to note Doctor Sommerman's computation of the viscosity index of the oil. We note also that he feels that our tests do not clearly prove that the process of oxidation is a cause for increased power factor. We agree to this, but on the other hand, we are not greatly impressed by the grounds of his doubt. What reasons has he for supposing that volatile products of themselves can cause an increase in power factor? The work of Piper in fact indicates that the addition of a wide variety of soluble oxidation products to an oil has little if any effect on power factor and loss. It seems to us that a far more probable and powerful cause is to be found in the continual process of chemical change during oxidation, and the temporary separation during this process of ions of opposite

sign. If such is the case, increases in conductivity and power factor are logical.

We agree with Mr. Halperin and others that in any studies of the oxidation process long periods are desirable. He makes the mistake, however, of comparing the conditions of our tests with those of his longtime tests on completed cables. His tests contain a variety of factors and influences on power factor and stability that we have taken great care to eliminate. His succession of temperature cycles particularly, introduces the whole question of the creation of voids and the resulting gaseous ionization. Gas bubbles and voids and gaseous ionization in the ordinary sense were apparently entirely absent in our tests. In fact we find in the result of Mr. Halperin's tests a strong corroboration of our conclusion that oxygen in small amounts in impregnated paper insulation has little or no effect as a deteriorating agent. In particular we repeat that in our experiments a constant supply of oxygen was kept up, which is definitely not the case in a closed cable, and that in spite of this fact, oxygen to the extent of 0.013 per cent by volume in the oil has an effect on the oil which is not greater than that caused by contact alone with paper and with metals.

The Current-Carrying Capacity of Rubber-Insulated Conductors

Discussion and author's closure of a paper by S. J. Rosch published on pages 155–67 of this volume (March section), and presented for oral discussion at the cables and research session of the winter convention, New York, N. Y., January 27, 1938.

H. B. Dwight (Massachusetts Institute of Technology, Cambridge): In 1935 and 1936 some thesis investigations were made by C. R. Boytano, I. I. Hochberg, and B. R. Souza at Massachusetts Institute of Technology, under my supervision, on the current-carrying capacity of single-conductor, 600-volt, rubber-insulated, braid-covered conductors in three and one-half-inch fiber ducts encased in concrete. The duct line was 30 feet long, with three ducts. Two sizes of samples furnished by the Simplex Wire and Cable Company were tested, with the following results:

Over-all thermal ohms per foot of duct, from the copper to the outside of the concrete, with the copper at 40 degrees centigrade.

Size	Number in Duct	Thermal Ohms per Foot (Degrees Centigrade for One Watt per Foot of Duct)
Number 4/0	1	5.0
Number 4/0	2	3.8
Number 4/0	3	3.4
500,000 circular mils	1	4.9
500,000 circular mils	3	2.9

The thermal ohms are slightly less than the values given, for temperatures above 40 degrees centigrade for the copper.

These results for fiber duct are of course not directly comparable with those for iron conduit.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): This is not merely another paper on "carrying capacity." It is the culmination of years of co-operative effort and research in which practically all who have studied the subject have had some voice. It should form the basis of future standard tables of carrying capacity and of future practice.

Mr. Rosch is to be congratulated on a fine piece of laboratory work and on his effective collaboration with other engineers in orienting his new data in relation to their data and experience.

D. W. Ver Planck (Yale University, New Haven, Conn.): The interesting paper by Mr. Rosch gives a much needed treatment of the subject of heat transfer from wires both in conduits and in the open. The study is based on the assumption that the heat transfer from the wires is entirely in the radial direction, as of course it is, for the major portion of any long uniform cable. One should not, however, lose sight of the fact that near the terminal of a cable there may be a considerable axial transfer of heat to or from the connected apparatus.

From the standpoint of this paper the case of greatest interest is where the connected apparatus tends to run hotter than the cable. This condition is encouraged by various apparatus standards which permit a maximum terminal rise of 30 degrees centigrade and in some cases even 40 degrees centigrade. Obviously, such rises above a 30 degree centigrade ambient will subject the end of the cable to temperatures from 10 degrees to 20 degrees centigrade in excess of the 50 degrees centigrade specified by Mr. Rosch as the limit for rubber insulation. It is the purpose of this discussion to indicate how great a length of the cable will be influenced by the high terminal temperature rise.

To derive the equation for axial temperature distribution let

x = distance along cable from terminal
T = temperature rise of copper at x
T_0 = temperature rise of terminal
q = heat generation per unit length
k = (radial) thermal conductance per unit length
R = (axial) thermal resistance per unit length

Upon applying the condition of heat balance to a differential length of the cable, there results the differential equation:

$$\frac{d^2t}{dx^2} - kRT = -Rq$$

Assuming that the length of cable extending from the terminal is great, the solution is:

$$T = \left(T_0 - \frac{q}{k}\right)\epsilon^{-\sqrt{kR}x} + \frac{q}{k}$$

indicating that the temperature rise decreases exponentially with distance along the cable from the terminal value T_0 to the value q/k which applies for conditions remote from the ends. A measure of the length to which the terminal temperature is propagated into the cable is $(kR)^{-1/2}$, a quantity which increases with cable size but in less than direct proportion. If the distance along the cable from one terminal to the next is not great, another solution taking account of both terminal conditions can be easily obtained.

Figure 1 of this discussion illustrates the use and checks the correctness of this analysis. A 4/0 cable in open air carrying 225 amperes is connected to a switch terminal having a rise of 35 degrees centigrade. The curve is calculated and the circled points are thermocouple measurements. The radial conductance per unit length k was deduced from Mr. Rosch's paper, table IV. The am-

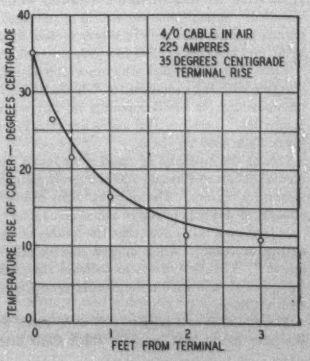


Figure 1

bient temperature was 25 degrees centigrade, and, while under these conditions the cable remote from the terminal attained a temperature of only about 36 degrees centigrade, a length of five or six inches near the terminal was subjected to temperatures in excess of the 50 degrees centigrade limit. Had the cable been worked to the limit calculated by Mr. Rosch's method, a still greater length would have been subjected to excess temperature, even though the safety factor included in curve *C* of figure 9 tends to reduce this length.

The possible overheating of the end portions of cables as a result of the high terminal rises permitted by various apparatus standards seems particularly worthy of consideration when it is remembered that these same end portions are likely to receive the greatest mechanical abuse during installation. It is hoped that the material in this discussion may help toward a better understanding of temperature conditions that sometimes exist near cable terminals.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): Rosch and those who worked with him are to be congratulated for giving us some valuable information on rubber-insulated conductors. The data presented, however, are not convincing that code rubber will have a long life when operating at 50 degrees centigrade. In their tests at 50 degrees centigrade the physical properties decreased. Perhaps the author is relying on the load in service actually being usually less than the rated load, or on the ambient temperature being less than 30 degrees centigrade most of the time.

In connection with building wiring, it seems to me that more thought should be given by the industry to the use of better grades of rubber instead of Code rubber, especially where there are possibilities of loading near the ratings or of high ambient temperatures. I have heard of some buildings where the rubber on the circuits was even two steps better in quality than Code rubber. The additional cost for a better grade of rubber insulation is small, especially in proportion to the total installed cost of a wiring installation, while the life of a wiring installation is on the average sharply increased by the use of better rubber.

It is interesting to note in figures 3, 4, and 5 that the rubber from the number 0000 cable stood up better than the rubber from the number 14 and number 16 wires. It would be interesting to know the author's explanation.

Referring to figure 9, which shows that the surface resistivity increases for cable diameters up to one and three-fourths inches, we have in the Commonwealth Edison Company been using a similar characteristic in resistivity for about ten years. Our curve is based on test data obtained for us by Barenscher at the University of Wisconsin. The curve is convex upward and has a resistivity of 400 for zero cable diameter, which becomes a value of 1,200 at two and one-half inches cable diameter. Mention of our curve has been made in the NELA meetings and in C. A. Bauer's article presented at the Great Lakes Section of the NELA underground systems committee on April 10, 1931 (Published in "1930–31 Report of Engineering Section," Great Lakes Division, NELA, Appendix XXXV, page 237). Our values are somewhat lower for the smaller cables than shown.

It would be of interest to know why the author plotted on figure 9, apparently, data from table VII instead of from table IV of his paper, because the latter data would result in a lower resistivity and a lower curve.

In contrast to the author's proposal to use the total area of two or three cables in a duct in connection with thermal resistivity, we have tried to take some recognition of the fact that the surface in the center of the combination of cables does not radiate heat. As a result, we have worked out a term for thermal resistivity for three cables based on two and one-fourth times the surface of one cable, the corresponding term being 1.83 in the case of two cables.

R. J. Wiseman (The Okonite-Callender Cable Company, Inc., Passaic, N. J.): Every engineer who has had occasion to compute the current-carrying capacity of rubber-insulated conductors installed in conduits has been puzzled by the difficulty of checking his calculations with the National Electrical Code. The other discussers have brought out the valuable work done by Mr. Rosch and his associates for the NEMA rubber covered building wire technical committee and we cable manufacturers are very grateful for the clearing up of many of the questionable constants such as radiation from braids and conduits of various sizes. To me, the real value to the paper comes from our ability now to be more certain of our calculations and the opportunity of revising the NEC so as to properly rate cables when drawn into conduits whether or not a single cable or several cables are used. Heretofore it was difficult to convince an electrical contractor or some utility engineers that the Code at the present time does not specifically state the current loading tables are for a single cable in a conduit. We are hoping that the Code tables will be revised and that they will give loadings for both single cables and three cables in a conduit such as table XI of Mr. Rosch's paper.

S. J. Rosch: Professor Ver Planck's comments with regards to the axial transfer of heat from connected apparatus to the terminating end of a cable, are very timely and to the point. This is a feature which has received very little consideration in the past and we recommend a study of his discussion by all those who are engaged in considering the question of heating of wiring in panelboards, circuit protection and the uniform current rating of service equipment.

Mr. Halperin questions the life of Code-grade rubber insulation at 50 degrees centigrade. As stated in the text, the investigation at 50 degrees centigrade was conducted on samples of cable submitted by eleven manufacturers. Figures 4 and 5 were chosen as typical of the extremes in performance when aged at 50 degrees centigrade. A study of figure 4 indicates that the trend is definitely parallel to the horizontal axis. This was true even when the aging was extended over a period of 19 weeks. From this it was felt that 50 degrees centigrade would give satisfactory life for Code-grade rubber insulations. Although space limitations prevented giving the performance data for the other nine manufacturers' products, it can be stated that they all showed the same trend as shown in figure 4.

We sympathize with Mr. Halperin's views on the desirability of using better grades of rubber insulation than the minimum grade now required by the National Electric Code. That the tendency is definitely in that direction can be seen from the fact that the Federal Specification Bureau's Specifications *JC* 106 and *JC* 121 now require a superaging type of rubber insulation for use on all wiring in projects under Federal supervision. This same type of insulation is also being considered by suitable committees in NEMA, IPCEA, and the ASTM subcommittee on rubber insulated wire and cable specifications. The National Electric Code has recently appointed a committee to study the trends in higher grades of rubber insulation, as well as other insulations which are capable of higher operating temperatures and possibly increased current ratings.

Regarding Mr. Halperin's question as to the reason why the physical aging of the 4/0 cables showed up better than the smaller sizes, we can only assume that this was a coincidence for manufacturers *A* and *B*. Had we given the data for the other nine manufacturers, it would have been seen that in six of the cases, the 4/0 cables showed up poorer than the smaller sizes.

As regards Mr. Halperin's questions on the values of B_b, the values plotted in figure 9 are the average values for B_b given in table IV and, since they are the average, they are more truly representative. The values given in table VII are for one condition only, namely, "horizontal open," and may be found under this column in table IV. During the computation of our results, we also used the areas suggested by Mr. Halperin, but they resulted in values for B_b that could not be fitted to a curve. It can also be readily seen that to use the areas suggested by Mr. Halperin, would result in more complicated formulas. Furthermore, so long as the "total" area is used in the computation of B_b and in the ultimate calculation of current-carrying capacity, no error is introduced in the result.

We appreciate the references given by Mr. Halperin concerning the values of *B* used by his company. We calculated several values of *B* from the data presented in Mr. Bauer's paper and found that on plotting them in figure 9, they practically fitted on curve *C*, the curve adopted for standardization. What is more surprising, how-

ever, is the fact that a curve plotted from the data presented by Mr. Bauer, almost completely parallels our curve *B*. It is regrettable that the factual data on which Mr. Bauer's formula for *B* is based was not given in his paper.

The comments of Professor Dwight are of interest, even though the data is not directly comparable to that obtained with iron conduit. They do, however, afford the author an opportunity to express his deep appreciation for the very excellent work done by Mr. C. R. Boytano, mentioned in Professor Dwight's comments. Mr. Boytano was responsible for the investigation of the thermal surface resistivity under the very able supervision of Messrs. A. C. Connell and B. Jore.

We also appreciate the kind remarks of Mr. W. A. Del Mar and Doctor R. J. Wiseman. The author was extremely fortunate in being able to discuss his results with the leading cable engineers in NEMA and the IPCEA. The present paper represents the combined engineering thought and effort of the wire and cable industry and, in conclusion, the author wishes once more to express his sincere appreciation to all those whose efforts were instrumental in making this paper possible.

Mechanical Uniformity of Paper-Insulated Cables

Discussion and authors' closure of a paper by K. S. Wyatt, D. L. Smart, and J. M. Reynar published on pages 141–54 of this volume (March section) and presented for oral discussion at the cables and research session of the winter convention, New York, N. Y., January 27, 1938.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Once again we are indebted to the Detroit Edison Company engineers for useful tools to assist in cable research. They have given us the radial power factor test, the hydrophil test, and now they give us the torsional penetrometer and the styrene wafer. We manufacturers are grateful for these means to assist us in giving to the industry the best cable that science and skill can produce.

The authors are undoubtedly right in looking for improvement in cable performance by the perfecting of mechanical uniformity. This goal has been the aim of cable manufacturers for many years, as evidenced by the improvements in taping and cabling machines, the use of caterpillar take-offs, pre-spiralled sectors, humidity control, and so forth. I doubt whether the styrene wafer will add anything to the knowledge which is the basis of these developments. So far, the styrene wafer has revealed nothing of that kind which was not known to the machine designers.

It is rather in more fundamental research that the styrene wafer will prove its usefulness. It has shown, for instance, that the paper tapes are practically tangential to round strands, thereby substantiating one of the claims made for the compact type of conductor, and it has definitely revealed the voids created by load cycles, both of which features in the past have been obscured by burring of the paper in cutting sections.

The number of inherent insulation failures in cables is now very small. If totally eliminated, the effect on the total outages would scarcely be noticed. If we leave out failures due to improper design of vertical cable ends, it is probable that a large proportion of the very small residual total of inherent insulation failures would be found to be due to unavoidable defects caused by the inherent fallibility of men and machines, rather than to any general condition susceptible of discovery by means of wafers. This is not to be interpreted as meaning that, in my opinion, cables are not susceptible of improvement. We shall have thinner walls, greater dielectric strength, greater power-factor stability, better sheaths, and many other improvements. I merely say that such improvements in mechanical structure of insulation as may be made in the future, will not materially reduce outages of cable.

It is, of course, in three-conductor, and particularly sector cables, that there is the most room for mechanical improvement, but life tests show that these cables are surprisingly close in quality to the single-conductor cables. Furthermore, the most carefully made laboratory-built cables are just as variable in their performance in load cycle tests, as the ordinary factory-built cables.

Inventors, realizing this condition, have sought to extend the voltage limits of cable, not by insisting upon impossible perfection, but by the more practical plan of accepting imperfections as inevitable and devising means to make them harmless. Thus Emanueli covers a multitude of sins by using a thin oil that maintains perfect impregnation, and both Bennett and Hochstadter effect the same result by putting the insulation under pressure. It seems to me that the authors of this paper are like people who insist on geometrically plane roads for safe and comfortable motoring, while others, like myself, prefer to have good tires, knowning that occasional road bumps are inevitable.

Referring to the curves of tape tension, the authors assume that uniformly high tension is the desideratum. It is not clear why they should hold this view as no evidence is given to support it.

I have seen cables with the most visibly nonuniform tape tension, that were perfectly satisfactory, and uniformly tight cables that failed. The tension of tapes is not a matter that can be considered by itself; the best tensions are tied up with manufacturing equipment and procedures, bending tests, oil viscosity, and operating temperatures.

We shall be better equipped to study this subject with the new tools the authors have given us, but it will take time to reach sound conclusions with them.

If the wafer method is to prove of great value, it will have to be greatly simplified, preferably along lines of inspection by reflected, rather than transmitted light, so as to eliminate the time and effort expended on making thin cuts.

The authors' study of tape staggering, is very much along the lines of a study I made in February 1930. Quoting from the unpublished report of that work:

"Twelve cases have been considered with staggerings in stages of 1/32 inch from cable *A* with tapes staggered the maximum amount to cable *K*, with tapes staggered the minimum amount. . . . It will be noted that they differ in two respects:

1. The recurrence of superimposed channels.
2. The length of the leakage path from conductor to sheath assuming the channels ionized.

"The recurrence of superimposed channels weakens the cable to radial stresses and a short leakage path weakens it to tangential stresses. Thus there are two potential paths of failure in parallel and on voltage-time test, the cable will fail along the weaker one."

A summary of the study of these cables follows:

The radial dielectric path is about 50 times as strong as the tangential path. Hence to compare these cables, we divide the length of the tangential path by 50 and compare it with the paper

Table I

(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Overlay†		Superimposed Radial Channels*		Shortest Leakage Path**	
Cable	32d's Inch	Per Cent	Per Cent	Mils of Paper	32d's Inch	Mils ÷ 50
A	10	43	50	110	430	269
B	9	39	14	189	429	268
C	8	35	20	176	386	242
D	7	30	33	147	343	215
E	6	26	10	198	300	187
F	5	22	25	165	257	161
G	4	17	11	196	214	134
H	3	13	17	183	171	107
I	2	9	12	192	128	80
J	1	4	9	200	85	53
K	0	0	4	210	0	0

* This includes channels with edges aligned, as well as those squarely superimposed.

** Paper thickness neglected.

† Tape is assumed 23/32 inch wide, with 1/32 inch gap, so that maximum possible overlay is 10/32 inch or $\frac{10 \times 100}{23} = 43\frac{1}{3}$ per cent. The per cent overlays are rounded to the nearest integer.

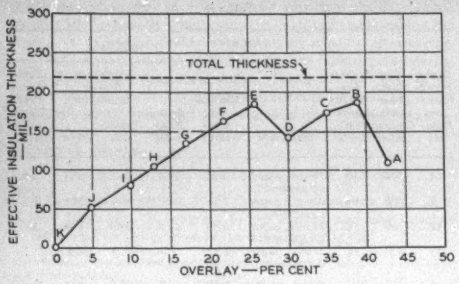


Figure 1

thickness of the radial path, as in columns 7 and 5 of the accompanying table I.

If we plot the lesser of these thicknesses (from columns 5 or 7) against overlay (column 3), we obtain the curve shown in figure 1 of this discussion from which it will be noted that there are substantially equal peaks at 26 per cent and 39 per cent overlay. The 26 per cent peak, however, gives better results due to the better bending characteristics of the cable.

Attempts were made to check curve *A* by voltage-time tests on specially made cable samples and while cables coming under the classifications of *A*, *H*, *I*, *J*, and *K* were definitely poor and cables *G* to *B*, definitely good, it was not possible to correlate the latter with the curve in figure 1, although the general trend was toward a maximum dielectric strength at *E* and *F*, rather than at *B*.

H. B. Dwight (Massachusetts Institute of Technology, Cambridge): May I ask if the mechanical tests described, particularly the test by making thin wafers showing the cross section, have been applied to large generator coils, and has information of interest been obtained?

R. J. Wiseman (The Okonite-Callender Cable Company, Inc., Passaic, N. J.): This paper again reports to us the valuable research work being carried out by the Detroit Edison Company in their desire to bring to our attention, tools or test methods which may be of help in our desire to improve the quality of our cables. However, in reporting the results of these test methods and the conclusions to be drawn from them, one must go slowly and cautiously because it is necessary to consider all the whys or wherefores that certain things are done, which ordinarily may be considered as a defect or shortcoming. For example: let us take the penetrometer and torsion tests which are supposed to indicate the degree of hardness tightness, or firmness of the insulation and the opinion is expressed that we should get a straight line plot of depth of penetration (figure 7) across the insulation. I am not so sure that we should get the same value for across the insulation. Perhaps a decreasing value as we go from the conductor outward or even an increasing value is better. We know in the taping operation that we have to adjust our tensions to prevent pinching or wrinkling of the inner tapes. Do we want a tightly wrapped cable which means a low value for penetration? If we do, we will get very little oil between the layers of the paper and this is as essential to us as oil in the paper itself is necessary if we hope to get good electrical characteristics. If too tightly wrapped we will not get good oil movement radially. If the paper is to loosely wrapped we will get drainage and voids. Therefore, we look for that wrapping which will give a well and uniformly saturated cable possessing low original ionization and high dielectric strength.

The development of the cable wafer is going to be very helpful to the cable manufacturer, as it gives him another tool for checking the mechanical setup of the cable. Here also, we must be careful about interpreting results. It does not necessarily follow that "comet's tails" unless distinctly more pronounced on one side than the other are due to the twisting of the conductor. There really is a comet's tail on both sides in the filler space. It can be due to the shape of the insulated conductor. A round conductor would show a longer comet's tail than a sector-shaped conductor. Also, it can be due to the use of too much filler material in order to get compactness and some of the filler will ride over the back of the conductor. If there is filler material between the conductors it is also due to too much filler and being forced into the space between the conductors. This is not serious as the filler is under high compression caused by the cabling operation.

Sometimes I wonder if we want the mechanical perfection that we hear about. We start with a good mechanical make-up in the factory and then as the authors say, we reel and unreel it, draw it into a duct, shape the ends around the manhole for splicing and finally it goes through the expansion and contraction due to loading. We upset the position of the papers and the oil moves but not entirely reversibly as in the case of oil-filled cables. If the tapes are wrapped tightly, we have a small amount of oil between layers. If too loose, we get drainage and poor electrical characteristics. If longitudinal movement of the cable is retarded, we get a forced radial expansion of the insulated conductors which will injure the insulation. A great deal is dependent on how a cable is handled and installed; in other words, the utility also has a responsibility where the cable leaves the factory in a good mechanical condition.

The oval type of cable overcomes some of the operating effects, but not installation. With this shape of conductor we get the paper along the minor axis stretching the necessary amount to take up the expansion of the oil and on cooling, forces the oil back again, thereby maintaining uniform saturation all the time. We also are able to hold down the internal pressure which develops during heating as well as prevent the cable from going to a high vacuum on cooling.

I am not able to go along with the idea that pretwisting of the conductors will eliminate the cabling problem. Figure 5, which is taken as an example of uniform insulation, does not have pretwisted conductors. We have made cables both ways and find it is not necessary to pretwist.

In taping, we not only look for the longest leakage path from conductor to sheath, but also the most effective use of layers of paper free of gaps. According to the table on page 151, one gets the impression that a 50-50 overlay is best. It is the worst, because we have only half the number of layers of paper effective due to the gaps lining up across the insulation. A 35–65 overlay is, on the average, about the best.

Let us not get the impression from the pictures shown in the paper that the cable manufacturers are sadly deficient in their ability to put out a quality product. If we did, the utilities would not be able to carry the loads at the voltages they do today and instead of the inherent failures of cables due to insulation being about ten per cent of the total failures, they might easily be over 50 per cent. We are constantly striving for both mechanical and electrical perfection, but there is an economic limit we can go to in view of the type of cable and how it is used. The chances of a large reduction in wall thickness are not promising in the near future.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): I ended my study of this interesting paper with mixed feelings and, as a result, my position is somewhat between that of the authors and that of some of the discussers. As usual and as indicated in the paper, we have co-operated and we have for several months been carrying on investigations as the result of the information first brought to our attention last spring by Mr. Wyatt.

The new tools developed by the authors are being used by many manufacturers and some utilities and should be of material assistance in improving the quality of paper-insulated cables. It remains to be seen, however, whether the use of such tools will eventually make feasible the radical reductions in the thicknesses of insulation of solid-type cables as prophesied by the authors. I will have to admit that as far as belted-type three-conductor 13-kv cable and single-conductor 69-kv solid-type cable are concerned, I do not see how improvements in the mechanical uniformity of the insulation will alone result in reductions in insulation thickness such as 30 or 40 per cent as implied by the authors.

Even though the failures due to insulation in cables made in the past 10 or 12 years are small in proportion to the total failures in underground systems, I do not agree with the implication of the remarks of one of the other discussers that there is practically nothing much more to be done as far as the insulation is concerned. There is still present the economic pressure to reduce costs, and one of the important ways of accomplishing this is to reduce the insulation thickness with safety.

As to the statement in the third paragraph of the introduction that one finds little or no information in the literature concerning compactness and uniformity of layer structure of insulation, I should like to point out that there was a tremendous amount of correspondence and oral discussion in the industry on the mechanical properties of insulation some 12 or 15 years ago. As a result, the American manufacturers practically eliminated the severe wrinkles of the insulation of multiple-conductor cables with sector-shaped conductors and the improper registrations of several tapes one on top of another. From time to time they have made further improvements in mechanical uniformity and I know of two important changes started in 1936. In addition, there are still arguments as to just how the tension and compactness of insulation should be. These tools of the authors should help settle these arguments.

There seems to be an idea in the paper that the effectiveness of insulation is reduced in exact proportion to the number of gaps that are in a straight line between any two electrodes. This implication is unwarranted.

As a general proposition, improvements in mechanical uniformity should apparently be of most benefit for three-conductor solid-type shielded cable with sector-shaped conductors and rated at 25 or 35 kv, the benefits decreasing down to the least possible benefit with oil-filled single-conductor cable.

C. L. Dawes (Harvard University, Cambridge, Mass.): The authors describe a process in which the paper tapes and the fillers of impregnated-paper cables become solidly embedded in their natural positions in transparent glass-like styrene. Thin cross sections or wafers permit a visual study of the mechanical structure of the cable, showing clearly any wrinkles, voids, butt spaces and the like which may be present. This process which involves in a high degree both chemical and physical technique gives engineers another method by which to eliminate the factors which are responsible for the all too frequent cable failures. The authors should be complimented on their important contribution to the art.

From many observations of cables subject to service conditions and accelerated life tests, I am in agreement with the authors' conclusion that the presence of voids, whether due to loose wrapping of the tapes or to butt spaces, does reduce materially the dielectric strength of the cable. With the expansion of the cable such as is caused by load cycles, the compound will tend first to vacate the voids because of the lack of capillary action existing in them. A very small amount of incipient ionization immediately produces mechanical impact which further drives the compounds from the voids, thus accentuating their effect. Not only is the potential drop across the voids reduced as stated by the authors, but also longitudinal stresses along the tapes in the neighborhood of the butts are developed. This is due to the fact that the voltage across a butt space is lower than that across the adjacent tapes, causing a voltage difference along the surface of the tapes, and possibly producing longitudinal creepage currents resulting in tacking and coring. (See C. L. Dawes and P. H. Humphries, "Ionization Studies in Paper-Insulated Cables, III," AIEE TRANSACTIONS, 1930, page 766.) This effect would be accentuated where two or more butt spaces are practically superposed, such as is shown in several instances in figure 14. As the authors state, when better precision in applying the tapes is attained, reductions in the thickness of insulation become possible without diminution in dielectric strength.

Investigation has shown that in many cases the thickness of the voids must be extremely small, for the voltage gradients at which ionization begins may be four or five times the ordinary critical gradient for air at atmospheric pressure. As early as 1919 Clark and Shanklin conducted a comprehensive investigation of this phenomenon in cables (AIEE TRANSACTIONS, 1919, page 489), and Dubsky studied the matter for insulations in general (AIEE TRANSACTIONS, 1919, page 537). My own investigations of a number of cables also show such high gradients with correspondingly very thin voids. These cables were never longer than 15 feet, inclusive of guards, so that the internal pressure could not have been far from atmospheric.

Table II

Cable Identification Number	Conductor (Thousands Circular Mils)	Insulation Thickness (64th Inch)	Insulation	Dielectric Constant	Ionization			Estimated Voids Thickness (Mils)
					Actual Kilovolts	Volts per Mil at Conductor		
						Insulation	Void	
1	500	16	Wood paper Compound	2.96	16.0	82.1	243	3.5
2	500	24	Manila paper Compound	2.96	21.0	78.9	234	3.7
12	500	16	Manila paper Compound	3.36	11.5	59.0	193	5.1
17	300	12	Wood paper Compound	3.24	7.0	47.3	154	7.1
19	300	12	Wood paper Compound	3.49	10.0	63.0	237	3.6
22	600	12	Wood paper Compound	3.20	12.5	79.6	255	3.1
24	600	12	Wood paper Oil	3.46	10.0	63.7	221	4.4

We also found that when impregnating compound was present in the voids, the gradient for initial ionization was practically double that with air alone (see Report of the Committee on Electrical Insulation, National Research Council, 1935, page 26). This increase in dielectric strength is apparently due to the presence of the vapors from the compound. There are little data on the dielectric strength of vapors under the conditions existing within impregnated-paper cable insulation. However, in J. J. Thomson's "Conduction of Electricity Through Gases," volume II, third edition, page 510, a table taken from the data of Bouty shows the dielectric strength of certain organic vapors. The data were obtained at pressures of from 0.0055 to 2 centimeters of mercury, which pressures are much lower than those ordinarily existing within cable insulation. The table does, however, show that the dielectric strength of such vapors is much greater than that of air alone, which confirms our experiments.

In the accompanying table II are a few typical data obtained with actual cables, some of which were new and others which had been in actual service. The estimated thicknesses of the voids were based on the available data for air, since no data for vapor-filled voids, particularly petroleum, of these small thicknesses and also at atmospheric pressure are available. It is very probable that many of the voids are thicker than estimated due to the presence of the vapors.

W. F. Davidson (Consolidated Edison Company of New York, Inc., Brooklyn, N. Y.): It was my good fortune to have followed, from their inception, the studies reported in this paper and I like to think that some of my words of encouragement were a factor in bringing them to a successful conclusion. Lack of factual information is a complete barrier to full engineering development. In the field of cables we have been seriously handicapped by not having exact knowledge of the inner mechanical structure of cables. Now at last it is possible for the cable designer to study the effects of various details of the manufacturing process and the user can determine the effects of installation and operating conditions; it is no longer necessary to guess as to the effects of many of these factors.

When we turn to the authors' interpretation of some of their observations, I am not able to agree with all that they have said. For cables of the 24-kv class, which form the basis for many of the comments, it seems to me that the ill effects of ionization and leakage path have been somewhat overemphasized. Care must be taken lest we allow ourselves to pay too much attention to correcting these

defects at the expense of other equally important details. Much progress has been made in improving the quality of insulation but the results, as measured by cable investment, are none too encouraging. One of the most important problems facing the cable engineer during the next few years is reducing costs. To me the only hope of accomplishing this lies in finding ways and means for operating cables at higher temperatures and with a greater range of temperatures. The designer must not be unduly handicapped in his efforts to accomplish this end.

C. J. Beaver (nonmember; W. T. Glover and Company, Ltd., Manchester, England): It is agreed by the authors, and may therefore be postulated for the purpose of the following notes that

(*a*) Ionization is practically the only inherent cause of failure in a reasonably well made dielectric.

(*b*) Ionization conditions are developed in cable dielectrics by physical processes incident to the use or working of the cable.

(*c*) The physical properties of the (solid type) dielectric are deficient for the purpose of preventing such development.

It follows that under reasonable working conditions the electrical life of the dielectric is dependent on its physical properties, and consequently the main question arising from the paper is as to the relative contribution of some lack of mechanical uniformity to the sum total of deficiency in physical properties.

In a solid-type lead-sheathed dielectric subjected to cyclical temperature changes, it is evident that at any temperature below the maximum, gaseous spaces (voids) must exist in the dielectric. The electrical stressing at which ionization will commence in these spaces will vary roughly inversely as the space dimension in the direction of the electric field, for a given set of conditions such as gaseous pressure, type of gas, and so forth.

Thus it is obvious that in a radially stressed solid-type dielectric, the most vulnerable gaseous spaces (voids) will occur in the butt spaces between the edges of adjacent laps of paper, where the radial dimension of the space will be equal to that of the paper thickness.

It is difficult to conceive a dielectric so poor in a mechanical sense that larger radial dimensioned spaces can exist between radially adjacent papers.

Hence it is clear that the stress at which ionization initiates depends on the butt space conditions, and it is this stress which controls the asymptotic or long-life voltage value of the dielectric.

The importance of the length and condition of the leakage paths (zigzag and step) appears to have been highly overemphasized in the paper.

The lengths of these paths and also the physical conditions existing between radially adjacent paper surfaces, do not affect the asymptotic or long-life voltage value of the dielectric, but merely influence the shape of the time-voltage curve above the asymptotic voltage value.

The Robinson theory confirms this as quoted by the authors on page 13: "Tracking along paper surfaces, which is now coming to be accepted as the mechanism of ionization failure, after a core has formed. . . ."

After load cycle testing there will be a general slackness or lack of mechanical pressure between papers in a radial direction, owing to the action of the radial flow of impregnating oil in a zigzag manner between the paper surfaces during the temperature changes.

Although a wafer of such a cable before and after the load cycles shows this difference, the increase in ionization in the latter sample will occur chiefly in the voids in the butt spaces caused by the process of oil expansion and lead sheath distension in an initially well-impregnated dielectric.

It has been proved by the writer in a very comprehensive series of experiments during the development of the gas filled cable (Paper No. 204, "The Gas Filled Cable," C.I.G.R.E. Session 1937, Paris) that electric failure of a cable dielectric invariably occurs through, and initiates in a butt space, and is also dependent on the butt-space thickness.

Under these conditions the most important dielectric feature which should be taken care of in the manufacturing processes is the avoidance of registrations between radially adjacent butt spaces, so that the space dimensions never exceed a single paper thickness.

In this connection special lapping machines (British Patent No. 182,510) are used by a British firm in which the cable is revolved, while the papering heads carrying the paper strip spools are stationary. The paper strips pass through slots in a sheet metal framework fixed to the machine, thus ensuring at all times that each paper strip is applied to the cable at a definite longitudinal position with respect to the adjacent papers. These arrangements also provide easy means of ensuring uniform tension of application of the paper strips.

It may be mentioned that the strips are preimpregnated, so that no question arises as to "conditioning" of the paper, nor of shrinkage wrinkling or other deficiencies arising in the manner referred to in the paper.

There is one other important point which should be watched in the manufacturing process and that is, that the mechanical structure of the cable dielectric should be such that the paper strips are not torn or cracked through during bending of the cable, so that large-radial-dimensioned gaseous spaces are avoided.

In this connection it is very desirable to avoid a 50 per cent overlap owing to the tendency of the paper between two alternate butt spaces to be cracked, and to become torn in consequence.

The authors do not appear to have considered this aspect, which in actual practice—from the installation point of view—is very important.

The authors' extreme optimism for future improvements and cost reduction in solid-type high-voltage cable is in direct conflict with present-day knowledge of the limitations of such dielectrics.

No amount of control of mechanical uniformity of cable manufacture can alter the stark physical facts that in a lead-sheathed cable subjected to temperature cycles, voids or gaseous spaces equal in volume to the oil expansion must exist at the low temperatures, and that the most vulnerable spaces will form in the butt spaces where the radial thickness of void is at a maximum.

The stress rating limitation of the modern solid-type cable dielectric depends upon the following factors:

1. The radial thickness of the butt spaces in turn dependent upon the minimum thickness of paper which it is feasible to use.
2. The maximum temperature to which the cable may be heated.

The above two factors affect directly the intensity of ionization in the butt spaces and set the limit to the permissible stressing, and conversely the loading.

A comparatively slight improvement in the homogeneity or uniformity of a dielectric cannot cancel out the whole physical problem entailed by the lack of reversibility of expansion and contraction effects, leading to ionization; and in face of the well-known necessity of restricting the temperature factor at even 60 kv it would appear quixotic to pursue working voltages up to 100 kv (as mentioned by the authors) with solid-type cable.

The scientific (and commercial) solution of the problem lies in the direction of the abolition of ionization in the dielectric, for example, on the lines of the "gas filled" cable (referred to hereinbefore), in which, without external compensating devices, and without restriction of loading temperature, ionization is completely suppressed to any designed extent, for instance, up to twice working voltage.

The authors' desiderata regarding reduction of insulation thickness and increased duct loading should be much more easily attainable along this line of development in which all constructional factors are capable of being definitely designed, and behavior in use is automatically controlled by reason of the reversible physical properties of the dielectric, preventing any permanent change (leading to ionization) under any working condition of the cable.

C. H. Jolin (nonmember; Merz and McLellan, Newcastle-on-Tyne, England): The description of methods used to investigate the mechanical construction of paper-insulated cables are very interesting. The three mechanical methods, "penetrometer," "push-out," and "torsion" are somewhat crude, in particular, the push-out method where the force required, besides varying with the tightness of the paper, will also depend on the roughness of the paper surface and the consistency of the impregnating compound. The torsion

method seems to be useful but it would be an advantage if an illustration could be given of the instrument used.

The wafer method is, I think, the best but it would appear necessary for this test to be carried out by skilled operators in a laboratory and under these conditions it should prove one of the most useful tests devised up to the present time. I think that the test will prove of most value to manufacturers as they will have the necessary facilities for making the tests, from the results of which they will be able to determine the effects of different methods of manufacture.

I gather from the paper that the author is in favor of the insulating space of the cable containing as large a proportion of paper to oil as is possible consistent with the cable being able to pass a reasonable bending test. I am in agreement with this for normal type of cable as it must assist in avoiding trouble due to compound expansion.

This requirement is not so important in other types of cable, for instance oil-filled cable is so designed that any gaps between papers will always be filled with oil and will, therefore, be harmless but even with this type of cable the smaller the amount of oil in the insulation, the smaller the oil reservoir capacity required to allow for oil expansion.

The gas pressure cable is in a different category as in some designs definite gaps are left between papers to allow free access of the gas under pressure to all parts of the insulation.

The author states that it should be possible to so improve the dielectric of the solid cable that it would be suitable for use at 100 kv or over.

I should like to know whether the author would recommend using solid cable at the same maximum dielectric stresses and temperature as is now used for oil-filled and gas pressure cable.

It appears to me that however well the cable is manufactured, some disturbance of the insulation will take place due to reeling and unreeling the cable on drums and handling the cable during installation. The spaces caused by these disturbances will remain in the solid-type cable whereas such spaces in the oil-filled cable and the gas pressure cable would be filled with oil or gas under pressure respectively and would thus be harmless. It would therefore appear that theoretically the oil-filled and gas pressure cables will be better than the solid type.

The illustrations accompanying the paper are interesting and show that delta-shaped-conductor three-core cable cannot be so satisfactorily insulated as a cable with circular conductors. The cable illustrated in figure 6 is so bad that it is hard to believe that any reputable cable manufacturer would turn out such a cable.

There is a point of minor interest I should like to raise with regard to figure 12. The conductor of this cable consists of part normal-size wires, together with a number of smaller sized wires in groups of three. Was there any particular reason for this method of construction?

Martin Hochstadter (Brussels, Belgium): My interest in the development published in this paper has been great for two reasons:

Firstly, because this is real pioneer work opening a new field of insight into questions of outstanding practical importance in electrical cable engineering, a field which curiously enough, has been more or less entirely neglected hitherto. Not only do I see great merit in the very discovery of such a new field and its courageous and successful attack, but also do I believe this to be of a refreshing effect on the minds of our younger generation of cable engineers. Seeing every day nothing but work on details of problems which have already been principally dealt with by others, they might be led to the conclusion that no exploration field was left to them. This paper gives evidence of white patches on the map of our technical knowledge.

Secondly, the author's problem has been occupying me during the greater part of the last ten years. Research on pressure cable was carried out at first with internal pressure, namely, with cables of such construction that the pressure medium was acting in or near the conductor. However, the pressure effect on the dielectric was found to be of rather an imperfect and unreliable nature in all such cases. After much research and speculation into the causes of such unexpected behavior it was recognized that the propagation of the pressure through the dielectric, while being rather complete and instantaneous when external pressure compresses the dielectric, is poor and uncertain when the dielectric expands under the influence of internal pressure.

Pressure in such a semisolid body is propagated from layer to layer. In the case of internal pressure this propagation consists in the elastic stretching of each individual layer. Therefore, it can only take place there where layers touch each other and are under about the same mechanical stress neutrally, that is, before the application of pressure. It is, therefore, evident that a uniform propagation of internal pressure is contingent upon uniformity of the mechanical structure of the dielectric and that the internal pressure may be stopped totally or partly at any point in the dielectric where tightly wound papers are followed by loose ones.

While at the time of which I speak the relation between propagation of internal pressure and mechanical uniformity of the dielectric was made evident, no exact measurements of the latter could be taken and it was not possible to overcome the difficulties for using internal pressure. Therefore, external pressure has been used hitherto for the pressure cable. However, the author's methods for the demonstration and exact measuring of the mechanical uniformity of the dielectric may well lead to such an improvement of the manufacturing methods that a sufficient and controllable mechanical uniformity of the dielectric be obtained for the use of internal pressure in pressure cables.

This is one of the practical possibilities which the author's methods may open in a particular field of cable making besides others for the improvement of electric cables in general.

Hugo Sonnenfeld (nonmember; Bratislava, Czechoslovakia): The present paper completes the impression experts have obtained by its predecessors. The wafer method is certainly contributing to the possibility to have a reliable look into the working of the cable, especially the insulation and the lead sheath.

Even though there are only a few pictures published in the present paper they are sufficient for showing the way to improve cable design. Compound migration being, as is well known, a very important factor, it is evident that the first step for making cable service more reliable than it is now, consists in reducing filler space as far as possible. The general practice to use sector-shaped conductors cannot be considered as the best way. This appears to be quite clear if thorough consideration is given to the wafers shown in the present paper. Filler spaces are at the minimum in the case only that the *theoretically exact sector shape* is used, such as illustrated in figure 4 of the present paper. The photograph of this wafer, however, makes it evident that the insulation is rather a nonuniform one, and this particularly due to the shape of the conductor. Not only is the conductor, on two sides, flat so that its surface does not follow the natural bulge of the paper but the unequal electrical stress on the shoulders on one side and on the sector back on the other as well as on the flat parts on third side, is in no case able to fulfill requirements of high-voltage cables. For these various reasons the theoretical exact sector shape (see figure 4) is not advisable for high-voltage purposes. In the paper the expression "extreme sector" is used for such a shape of conductor, see page 148. We should not forget that this shape of sector is the only one which brings the filler spaces to their minimum.

If, however, the sector shape deviates from the theoretical exact "extreme sector" form, we come to designs such as is illustrated in figure 5. Here the gross irregularities, discovered in figure 4, are absent, the shoulders of the conductor being less sharp and the conductor more able to conform to the natural bulge in the paper. But all this is accompanied by the serious disadvantage of filler spaces evidently becoming larger. For this latter reason such cable does not represent the best possible design.

A round conductor offers little difficulty. It is to be expected that all disadvantages illustrated by figure 4 will not be present if the same machines and the same manufacturing method are applied but with a round or oval-shaped conductor. No doubt, the circular or oval shape is in any respect the best form of the conductor. If small fillers are used, resulting in a triangular shape of the lead sheath (so-called *S.O.* type cable) the reduction of the possibility

of compound migration improves the properties of the cable and the cost of the cable containing circular (or oval) conductors is brought down to the cost of the cable containing sector-shaped conductors.

Thus the application of round (or oval) conductors together with the application of the triangular shape of the lead sheath makes available the following advantages of the cable:

The volume of oil compound causing expansion is reduced.

The radial resistance to oil flow is brought down to a minimum.

The thermal resistance is equally brought down to a minimum.

The facility to wrap paper with exact regularity upon the conductor is increased.

No pretwisting is necessary.

K. S. Wyatt, D. L. Smart, and J. M. Reynar: The authors are grateful for the favorable reception accorded the methods proposed for studying the mechanical uniformity of paper-insulated cable. It appears, however, that although the tools themselves have been accepted almost without qualification, the interpretations which were made in terms of design, manufacture, and service life have furnished many points of controversy. The primary purpose of the paper was to offer new test methods for obtaining data which might be of assistance in studying the relative merits of different types of construction and in determining the causes of insulation failure. Since the value of the wafer method depends, as in the case of X-ray photography, on correct interpretation, it appeared advisable to present tentative interpretations of cable wafers as samples of what to look for in the wafers and of how irregularities might be traced to original sources. A certain amount of theory was necessarily involved in these interpretations. Space limitations necessitated a rather cursory treatment of this phase of the paper with the result that many unintended inferences were drawn by readers. In addition, it was only to be expected that, in view of the relative newness and limited use of the method, the interpretations would be questioned as were those of X-ray photographs in the early days of their use. Furthermore, the necessary omission of a large number of illustrations representing reasonably good cable wafers undoubtedly caused an erroneous impression in some minds regarding our estimate of the quality of the average modern cable.

Several discussers point to the apparent futility of producing mechanically perfect insulation in view of the amount of relatively rough handling the cable undergoes during installation. The authors direct attention to the fact that the wafer method now enables us to evaluate the effects of such treatment. Time has permitted only meager investigation of this phase of the problem but, for what they may be worth, the results obtained do not indicate any serious damage to be sustained by a mechanically well-built cable when installed by modern methods.

If it appears, as stated by several discussers, that the paper overemphasized the effects of ionization and attached too much importance to the length and condition of the leakage paths, it is because the facts revealed by a careful study of scores of cable wafers lead, first, to a critical inspection of previously held theories of the mechanism of cable failure and, finally, to a tentative revision of these theories to better fit the observed conditions. Among these conditions were three which were frequently observed and which experimental evidence and theoretical considerations indicate have an important bearing on insulation breakdown. Two of these conditions involve butt-space distribution as it affects effective solid insulation thickness and minimum leakage path, and the third involves thick interlayer spaces caused by loosely wound insulation. An explanation of the part played by these factors in insulation failures would entail much theoretical discussion and would perhaps, be out of place here. The discussion by Professor Dawes, however, may serve to partially explain the phenomena responsible. The following briefly summarizes the conclusions of the authors as a result of their initial investigations:

(*a*) Ionization is held to be the chief cause of inherent insulation failure.

(*b*) The theory of D. M. Robinson that breakdown starts at the conductor and proceeds slowly through the insulation by a coring and tracking mechanism is accepted with reservations as to the importance of voids in the middle of the insulation wall.

(*c*) Conditions conducive to ionization are present in much cable as manufactured and may be aggravated due to service or to improper handling during installation. (Initial voids, even though they be filled with oil and thus do not cause high *initial* ionization, are considered to be conducive to ionization.)

(*d*) The development, during service, of conditions conducive to ionization may be minimized by proper design and manufacture.

(*e*) The inevitable presence of butt spaces at the conductor and other inherent weaknesses in the insulation of solid-type cable are not arguments against the elimination of other defects since many of the latter add to the basic inherent weaknesses to further decrease the over-all insulation efficiency.

(*f*) As the quality of the cable insulation is made more uniform due to precision methods of manufacture, the thickness of the insulation may be reduced because it is no longer necessary to provide a factor of safety to take care of avoidable but uncontrolled weaknesses.

It is seen that we do not agree in toto with Mr. Beaver's postulates (*b*) and (*c*).

The elimination of registrations and also of interlayer gaps is bound up with the taping machinery. We are in agreement with Mr. Beaver as to the advantages of certain types of "lapping machinery," but we must point out that they possess several apparently inherent disadvantages, among which is slowness of taping. If the paper is impregnated prior to taping, the trapping of gas between adjacent layers of insulation is an additional disadvantage. The design of taping machinery plays a most important part in the quality of cable insulation and the wafer method permits a visual study of the effects of the various design factors. For best results it is the belief of the authors that taping machines should have the following characteristics:

1. Direct drive throughout with as few gears as possible, since these introduce backlash.

2. Slow, smooth, but positive starting, without slippage, and brakes which stop the machine smoothly but reasonably quickly.

3. Direct synchronization between capstan and taping heads to eliminate the possibility of backlash or slippage.

4. A tape tension control in which centrifugal effects are absent and in which the tension of the tapes is independent of the amount of tape on the pad.

This is a subject deserving of much space. Suffice it to say here that hydraulic drive and synchronization appear to the authors to offer the best solution of the problem of precision taping at reasonable cost.

Mr. Del Mar and Doctor Wiseman infer that a uniform tape tension from conductor to sheath was recommended. Such an inference was not intended and may have been due to the fact that the torsion curve shown for uniform insulation was fairly level from conductor to sheath. The only relatively uniform cable which we had examined by means of the torsion test at the time the paper was written did not have the drooping characteristic from conductor to sheath which we believe to be desirable from the standpoint of ability to withstand bending without distortion. The same discussers also question the desirability of a high tape tension with a corresponding thin oil film between tapes. We believe, and support is given to this viewpoint by the discussions of Mr. Hochstadter and Mr. Jolin, that this film should be as thin as is consistent with good bending characteristics for a number of reasons. First, less oil is present and void formation is less likely to occur as a result of differential thermal expansion. Obviously tracking in service would be expected to be retarded or possibly eliminated. Second, the thinner the oil film, with other things equal, the less the comet's tail effect produced during cabling. Third, a very thin oil film which will permit successive paper layers to come into practically direct contact permits capillary effects to work to greatest advantage to distribute oil during impregnation, to prevent imigration and drainage during operation, and to return oil to the interior of the structure as the cable cools.

Several discussers have wrongly inferred that the study of cable wafers has led us to recommend a 50-50 overlay. The fact that with such an overlay the effective solid insulation thickness is only 50 per cent, coupled with the observation that due to the superposition of alternate butt-spaces the paper between has a tendency to tear when the cable is bent, would not permit such a recommendation. No attempt has been made by the authors to evaluate the relative importance of effective solid insulation thickness and minimum leakage path as factors in insulation failure for the purpose of selecting the best overlay. For this reason the report of the study

of tape staggering made by Mr. Del Mar is particularly interesting. Accepting, for the sake of this discussion, his figure of 50 for the relative strengths of the radial and tangential dielectric paths, we do not believe that figure 1 of the discussion is a correct picture of the variation in effective insulation thickness with overlay. In the first place, it seems apparent that the values given in column 6 of table I should read as follows: 430, 387, 344, 301, 258, 215, 129, 86, 43, and 0. The figures in column 7 should be changed to correspond. Furthermore, if it be assumed, as seems reasonable, that failure may proceed, not only along *either* the radial path *or* the tangential path, but along a combination of *both* types of path, neither column 5 nor column 7 represents the shortest equivalent leakage path for many overlays. For example, with an overlay of $^{9}/_{32}$ inch or 39 per cent, the radial path through a tape to the butt space in the next layer would be less than $^{1}/_{10}$th the length of the

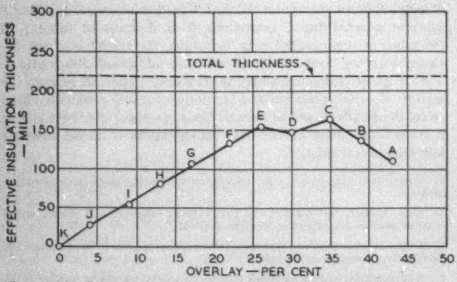


Figure 2. The effect of overlay on the effective insulation thickness

tangential path to the same layer, and failure would occur by alternate ruptures of a tape and tracking to a point opposite the nearest butt space in the next layer. The effective insulation thickness would then consist of 110 mils of paper plus, 1,302 mils of leakage path which would total 136 mils equivalent insulation thickness. This is less than the figures in either column 5 or 7 for this overlay. Similar calculations for $^{5}/_{32}$-inch and $^{6}/_{32}$-inch overlays, when combined with the changes in column 7 mentioned previously, result in the modified curve shown in figure 2. This curve is markedly different from that shown in Mr. Del Mar's figure 1 and, incidentally, appears to fit the results of his voltage-time tests more closely, although we cannot agree with Mr. Del Mar's and Mr. Beaver's use of the results of voltage-time tests as an indication of the behavior of cable in service.

Mr. Jolin points out that difficulties are encountered in insulating sector-type cable and Mr. Sonnenfeld discusses the effect of the conductor shape on the ease with which a uniform insulation may be obtained, and on the filler-space volume. These are questions which the wafer method of examination should be of inestimable value in answering.

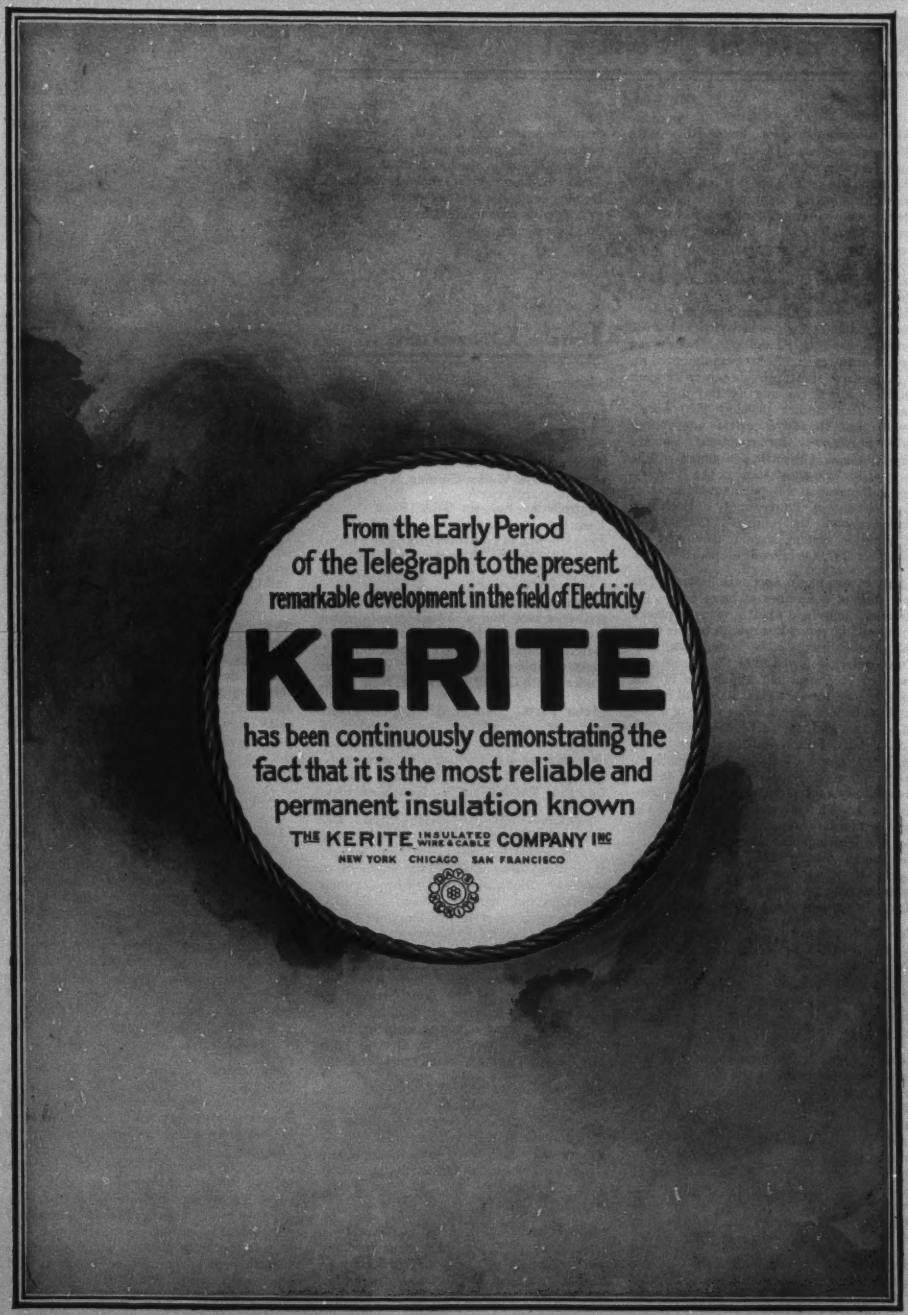
We agree with the discussers that much can and should be done to simplify the making of wafers. In his oral discussion, Mr. Meyerhoff described one method of simplifying the preparation of wafers from the styrenated cable sample. In this method, very thin wafers were cut with a band saw without finishing the faces on a lathe. The opacity of the sawn faces was eliminated by coating the wafer with a thin cable oil and mounting it between flat glass plates, care being taken not to wipe off all the surplus oil from the wafer. The development of a type of styrene or other material having a lower polymerization temperature and a shorter setting time would prove to be an important step. It is also suggested that the time of extraction might be shortened by permitting the styrene to trickle through the insulation continuously rather than to wash out the oil by the cyclic bath method described in the paper.

The apparatus originally used for making the penetrometer and torsion tests was admittedly crude. Since the paper was presented, however, the instruments have been considerably refined and combined into a single instrument which will be marketed by a well-known scientific instrument manufacturer. An article on the use of the compactness tester is being prepared, and it is expected that it will be published shortly in the technical literature.

In answer to Mr. Jolin, the authors are unable to give a reason for the design of the conductor shown in figure 12 of the paper. This cable was manufactured over eight years ago. It is believed that there was no intention of using the space between the strands as an oil duct and it is apparent that oil expansion would be more severe because of the large oil volume.

Mr. Dwight's question will have to be answered by others. So far as the authors know, such an application of the wafer method has not been made. The method has been used to advantage on trunk telephone cables in several countries. We believe it has a useful application in the study of many laminated dielectrics where uniformity of structure is of importance.

Our acknowledgment unintentionally omitted a word of appreciation for the support we received from engineers of other utilities. Possibly without this encouragement, this research could not have been carried to successful fruition.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Industrial Notes

New Locomotives for Penn RR.—Both Westinghouse and General Electric have each recently received contracts to supply the electrical equipment for ten new high speed locomotives to be used in passenger service on the Pennsylvania Railroad between Harrisburg, New York and Washington. These two contracts, which total approximately $3,400,000 embrace part of an expenditure of more than $8,000,000 by the railroad for new rolling stock. The twenty new locomotives will be designed to operate at 100 miles per hour, instead of the present speed of 90 miles per hour. Six twin motors, each 770-hp twin-mounted on a single drive shaft, provide power for each engine. When running at 100 miles an hour, these motors develop 4620 horsepower, but they can provide more than 8,000 horsepower for spurts of tractive effort. General Electric equipment will be built at its Erie plant; most of the Westinghouse apparatus will be manufactured at East Pittsburgh. Power supply stations used exclusively for the railroad's 132,000 volt distribution system have a combined capacity of 387,000 kilovolt amperes.

Utility Places Large Appliance Order.—The first four of a number of large orders for electrical household appliances were placed with manufacturers last month by the Consolidated Edison Co. of New York, Inc. These orders, believed to be the largest ever awarded for household appliances in this country, call for about 500,000 small household appliances, with a dollar value of about $3,500,000, and are to be campaigned by Consolidated Edison and its affiliated companies in co-operation with their nine hundred approved appliance dealers in the greater city and Westchester starting September 1. The successful bidders for the first four orders were the General Electric Co., the Westinghouse Electric & Mfg. Co., the Proctor Electric Co., and the Artistic Lamp Mfg. Co. According to these manufacturers, the orders will require the employment of more than 1500 additional men.

New York Office for Chance Co.—Paul K. Rhoads is in charge of the New York City office recently opened by the A. B. Chance Co., of Centralia, Mo., to promote the sale of the Chance-Tips Tool Co. products in that territory. Mr. Rhoads was sales manager of the Tips Tool division.

General Electric Business Report.—Orders received by General Electric Co. during the first six months this year amounted to $128,223,823, compared with $217,265,619 for the same period last year, a decrease of 41 per cent. Sales billed for the first half of 1938 totalled $130,910,638, as against $171,076,645 for the first half of 1937, a decrease of 23 per cent. Orders received during the second quarter of 1938 amounted to $62,847,423, compared with $111,518,589 during the corresponding quarter of 1937.

Kingsbury Machine Appointments.—Nelson Ogden has been appointed general manager of the Kingsbury Machine Works, Philadelphia, succeeding H. A. S. Howarth, resigned. The management of this bearing business is now in the hands of Mr. Ogden, Arthur B. Lakey, chief engineer, and A. K. Dennis, controller and secretary, according to a recent announcement by Albert Kingsbury, president.

Trade Literature

Insulators.—Catalog, 48 pp. Describes "Pyrex" power insulators and line hardware. Cross-section illustrations and complete specifications for all types are included. Corning Glass Works, Corning, N. Y.

Controllers.—Bulletin GEA 1724A, 12 pp. Describes construction and operation of a complete line of controllers for synchronous motors. General Electric Co., Schenectady, N. Y.

Instruments.—Sup. 3, Cat. 48, 2 pp. Describes a new line of 3-inch square, flush mounting, panel type a-c and d-c ammeters, milliammeters, microammeters, thermocouple-ammeters and voltmeters. Roller-Smith Co., 12 Park Place, New York.

Motor Parts. Catalog 53, 192 pp. Lists parts for motors, fans, and controllers of standard manufacturers, also supplies such as insulating materials, magnet wire, tools, etc. Prices included. Reading Electric Co., Inc., 200 William St., New York City.

Insulators.—Bulletin 657-H, 2 pp. Describes "Clamptop Insulators," which are pintype insulators that use a clamp instead of the usual tie wires to hold the conductor in position. Illustrations show why the units are radio interference-free and how they may be installed while the line is in operation. Ohio Brass Co., Mansfield, Ohio.

Oil Circuit Breakers.—Cat. Sec. 5, 12 pp. Describes motor-operated, style RWE, oil circuit breakers of the multi-break type with six breaks in series per pole, for use on a-c power systems at voltages ranging from 115 kv to 287 kv. Pacific Electric Mfg. Corp., 5815 Third St., San Francisco, Calif.

Switches.—Catalog 9, 12 pp. Describes type R-2 rotary switches for instrument and control use. These switches are flexible in design and completely cover the field of apparatus control, whether the requirement is standard or special, on circuits up to 600 volts. Roller-Smith Co., 12 Park Place, New York City.

Steam Turbines.—Bulletin B.2137, 12 pp. Describes type C general purpose turbines with capacities ranging from 5 to 500 hp at turbine speeds of 1000 to 5000 rpm. Installations of turbines of this type driving a circulating pump for condenser, draft fan, boiler feed pump and centrifugal pump are illustrated. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

High Voltage Switchgear.—Bulletin 638, 12 pp. Describes high voltage air switchgear. This I-T-E line has been extended to include circuit breakers for service on 2500–5000-volt circuits; interrupting capacity up to 150,000 kva. These circuit breakers are mounted in trucks which are held in engagement with an enclosed, insulated bus. I-T-E Circuit Breaker Co., 19th & Hamilton Sts., Philadelphia, Pa.

Valves.—Reference Book 38, 48 pp. Describes a complete line of boiler blow-off valves, several new lines of lift-plug valves, dimensions, tables; a new line of semi-steel 500 pound oil, water and gas valves for the oil industry. Included are prices; complete dimensions, tables and uses for valves in all industries, and suggested metals for special service conditions. Homestead Valve Mfg. Co., Coraopolis, Penn.

Network Protectors.—Descriptive Data 35–600, 24 pp. Describes light-duty, roll-out unit network protectors. For better voltage regulations, improved service continuity decrease in light flicker and extreme flexibility of the a-c secondary network, this protector may be used in the medium density overhead and lighter density underground areas as the use of heavy appliances and lighting increases. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Test Switches and Accessories.—Catalog, 120 pp., consisting of 4 bulletins in a suitable ring binder for easy reference. Bulletin 381 describes "Roto-Test" switches for relay testing, meter testing, and transfer switches. Bulletin 382 describes meter and relay knife-type test switches. Bulletin 383 describes metal meter enclosures, connection boxes and "Slide-A-Link" test blocks. Bulletin 384 describes meter and relay testing accessories. Meter Devices Co., 1001 Prospect Ave., Canton, Ohio.

Motors.—Bulletin 1156A, 20 pp. Describes large induction motors of both bracket bearing and pedestal bearing types. Numerous installation photographs are included. Control equipment applicable to squirrel cage and wound rotor motors is also covered. Bulletin 1165A, 16 pp. Describes design and characteristics of bracket bearing type synchronous motors, together with control equipment. Included is a discussion with vector analyses of the use of synchronous motors for power factor improvement. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Switchboards. Catalog, 36 pp. Describes "Multumite" switchboards. These are completely enclosed structures containing all the apparatus necessary for the control of distribution from one or more sources to a group of feeders. Ample interrupting capacity and strength are provided to take care of the most severe short circuit. Accessibility for the inspection of all parts is obtained by the use of removable panels and withdrawal type circuit breakers. The bulletin is profusely illustrated and shows installation arrangements of breakers and other equipment. I-T-E Circuit Breaker Co., 19th & Hamilton Sts., Philadelphia, Pa.

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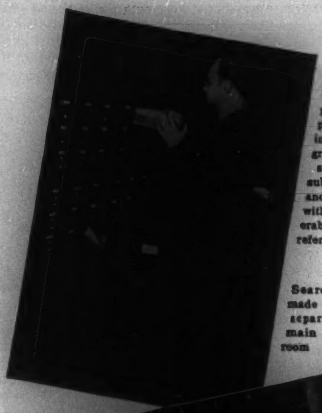

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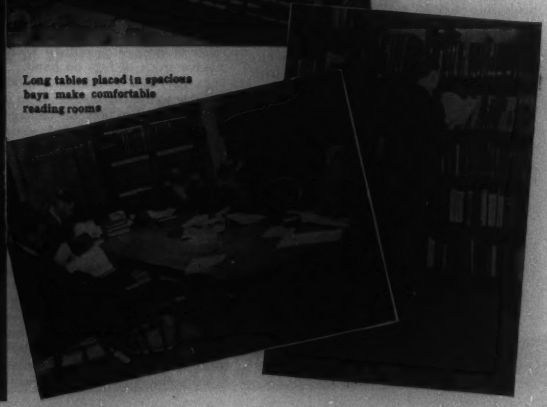

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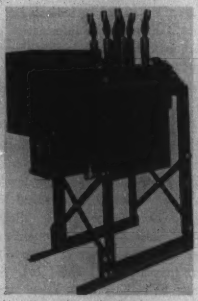
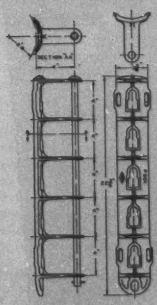


dustrial as well as central station and railroad applications, the new circuit breaker is particularly well adapted for use in steel mills on feeders, motors, incoming lines, and at other places where frequent operations are necessary. The breaker may be operated either electrically or manually; it interrupts the circuit within eight cycles (0.133 sec.).

Secondary Rack.—A universal type, 8-inch spacing, secondary rack, type PA601, introduced by the Malleable Iron Fittings Co., Branford, Conn., possesses several new features. The rack assembly has for its main part the one-piece P601 malleable rack casting, without riveted or welded joints, assuring maximum strength. Slotted bolt holes are so shaped as to permit placing through-bolts in the pole with the head projecting slightly and still permitting the rack to be mounted on these through-bolts without dismantling. There is no need of an upper extension under any circumstances with this construction, and the lower extension is provided merely for those cases where a lag is preferred at this position instead of a through-bolt in one of the spaces above it. Exhaustive tests indicate strength well beyond any service requirements. The malleable construction with hot-dip galvanizing assures long life.



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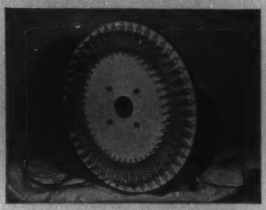
Special Cable Insulations.—The Okonite Company, Passaic, N. J., has developed several special insulations which have been successful in solving many familiar but troublesome cable problems. Okoprene, a synthetic rubber-like compound having high dielectric strength, is extremely tough, moisture-resisting and unaffected by oils, solvents and other chemicals. It is suitable for portable cables and for cables drawn into ducts filled with contaminated water. It also resists the effect of sunlight and heat, offering excellent protection for exposed aerial and pole riser cables. Another synthetic compound, Okoseal, provides a flexible, leather-like insulation and sheath that is non-inflammable yet moisture, oil and chemical resistant. Since it requires no outer braid, Okoseal is especially adaptable for use on switchboards and in other locations where fire risks must be reduced to a minimum. For circuits that operate with extremely high ambient temperatures, conductors insulated with Okoglass (a glass fibre insulation applied in the form of rovings) are available. When installed in dry locations near such equipment as boilers and ovens this insulation is protected by non-inflammable Okoglass braids. In hot locations where condensed moisture is present, it is protected with a lead sheath. Okoglass cables can be operated at copper temperatures up to 200° C and are capable of withstanding considerable abuse.

Cable Connector.—The "Varilug" is recommended by the manufacturer—Burndy Engineering Co., Inc., 459 E. 133rd St., New York City, for connecting a wide

range of cable sizes without keeping an extensive stock of lugs on hand. The Varilug's flattened U-bolt not only makes it possible to use this connector on many sizes of cable, but also prevents damage to highly compressible flexible and extra flexible cables. Vari-connectors, in addition to the lug illustrated (type VA) are also furnished in the form of angle lugs, T-connectors, end-on-end joints, elbows, stud clamps, reducers, etc.—all employing the flattened U-bolt principle.

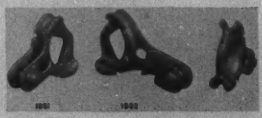
Motor for Educational Purposes.—A practical laboratory unit for demonstrating the fundamental operation of a-c motors has been developed by the Westinghouse Electric & Mfg. Co. This unit has the unique arrangement of a standard squirrel-cage motor with a special circular terminal board. Inlaid under the top surface of the board is a representation of the 48 slots in the primary of the motor together with numbered lines to show the actual location of the coils in the slots. The ends of these 48 stator coils are connected on the rear of



the board to the studs shown as the ends of the coils when looking at the front of the board. This makes it possible to interconnect the coils in any desired manner by the use of leads or jumpers on the face of the board. The motor may be connected for either 2, 4, 6, 8, or 10 poles and for either two-phase or three-phase power supply. The engineering design student is able to calculate resistance, reactance, and leakage constants and to check the calculated performance against that actually obtained in the laboratory.

Columbia Electric Expands Generator Line.—The Columbia Electric Mfg. Co. Cleveland, O., has expanded its line of a-c generators which are now available in sizes ranging from $1^1/_2$ kva up to and including 300 kva, in a wide range of speeds and suitable for direct connection to gas, gasoline, or Diesel engines. These generators are furnished with direct connected exciters or for excitation drawn from an external d-c source. When generators are furnished with direct connected exciters, a special compounding type, automatic voltage adjuster is available. This adjuster will maintain the voltage within plus or minus 5 per cent for average load conditions. It has no moving parts, vacuum tubes, or contacts.

Clamps.—Two types of dead and angle clamps are being offered by the Royal Electric Mfg. Co., 619 E. 40th St., Chicago, Ill. Light line clamp No. 1861 provides a simple method for dead ending angle and Tee construction with a 6-inch diameter suspension insulator. It is of malleable iron, hot-dip galvanized. The conductor groove is 3 inches in diameter and will



accommodate any conductor whose outside diameter does not exceed 21/32 inches. Dual duty clamp No. 1862 is a hot-dip galvanized malleable iron fitting which is especially suitable for Tee connections and can also be used on dead ends and angles. The conductor grooves are adequate and suitable for all conductors with maximum outside diameter not exceeding 21/32 inches.

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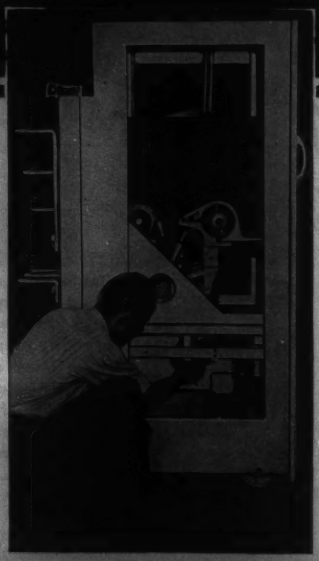

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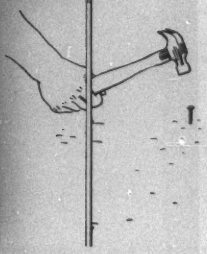

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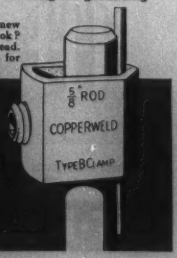

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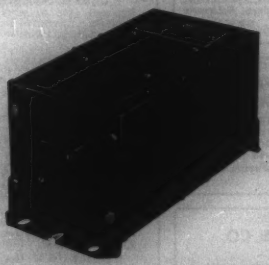

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Users of 200,000 M.I.F. Through-bolt Guy Hooks during 1937, including a majority of the operating companies in the U.S. and Canada, tell us their anchor guy construction has been simplified and improved with considerable savings over former methods. Operating Superintendents and Engineers sending us data on guy strand sizes and ratings will receive in return samples with specific recommendations.

Guy Hooks—Three principal types in addition to P134 Crossarm Guy Hook. P135 rated at 13,000 lbs. on ⅝" through-bolt is also approved for R.E.A. projects. P133 rated at 20,000 lbs. on ¾" through-bolt. P132 rated at 40,000 lbs. on 1" through-bolt. Make up guy loops on the ground and save time of the whole gang. Prices as low as 15c each in quantity.

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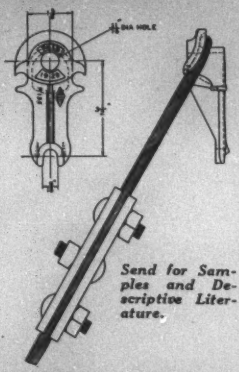

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DETACH HERE

A.I.E.E. MEMBERSHIP

To the National Secretary, A.I.E.E.
33 West 39th Street,
New York, N. Y.

_____ Date

The following persons are, in my opinion, qualified to become members of the Institute, and I recommend that they be furnished with application blanks and other pertinent information.

_____
NAME (please print)

_____
Position and Company Address

_____

* * *

_____
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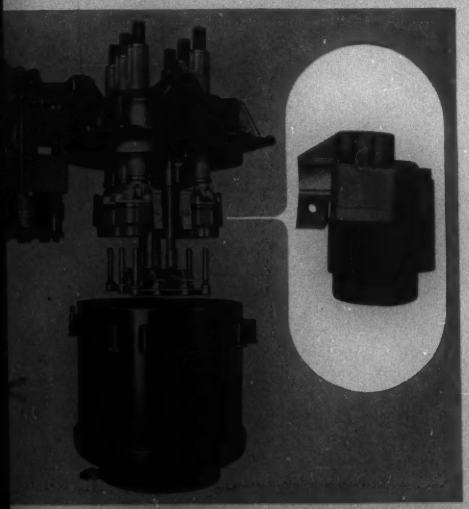

CHOSEN FROM TWENTY-THREE separate and distinct designs for an interrupting device was the "Ruptor," shown here at the right. After exhaustive tests, it was developed to its present high efficiency and incorporated in oil circuit breakers, such as the one shown here.

● High interrupting capacity! Low maintenance cost! Fewer contact replacements! More hours of service between inspections!

That's what you get with Allis-Chalmers Oil Circuit Breakers with Ruptors for high voltages. For Ruptors extinguish arcs . . . *in a hurry*! Their "QUICK-QUENCH" action reduces oil carbonization and contact replacement . . . eliminates high maintenance and inspection costs! You get consistent operation without constant attention.

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It is recommended that oil-filled cable be given consideration in plant problems involving high-voltage, underground cables. We offer an active, practical engineering service for assistance in such studies. Our bulletin on oil-filled, paper insulated cables will be mailed upon request.

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